FRANCISCAN AND RELATED ROCKS, AND THEIR SIGNIFICANCE IN THE GEOLOGY OF WESTERN CALIFORNIA

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Abstract

A heterogeneous assemblage of eugeosynclinal rocks found on the San Francisco peninsula has long been variously referred to as the Franciscan Series, Franciscan Group, or Franciscan Formation, and other rocks throughout the Coast Ranges have been correlated with these on the basis of lithologic similarity. The predominant rock is graywacke, but shale, altered mafic volcanic rock (greenstone), chert, and minor limestone are a part of the assemblage. Also included are metamorphic rocks of the zeolite, blueschist (glaucophane schist), and eclogite facies. Ultramafic rocks, largely serpentinites, are an integral part of this eugeosynclinal assemblage, but they are excluded from the Franciscan Formation as they intrude most of the other rocks in it. This assemblage of rocks was deposited in one or more deep marine troughs, probably on a basaltic substratum or peridotite.

This eugeosynclinal assemblage underlies a major part of western California and is prominently exposed in the Coast Ranges. Its known area of outcrop is 15,000 square miles, and its total terrestrial and offshore extent may be 75,000 square miles. Its total thickness cannot be determined by normal stratigraphic methods, but is probably more than 50,000 feet.

The assemblage of rocks grouped together as the Franciscan ranges in age from at least Late Jurassic to Late Cretaceous, but rocks deposited during the entire age span generally are not present in any one area. Although some discrete areas of older or younger Franciscan rocks are recognized, the data available now allow us to describe the characteristics of each prominent kind of rock only in general terms applicable to the entire assemblage. Thus, although some rocks, for example the greenstones, may be consistently different in the older and younger parts of the Franciscan, we are not yet able to discern this, and we must, therefore, describe the variations without attaching age significance to them.

The graywacke is dominantly medium grained and typically is interbedded with minor shale and rarer conglomerate. Bedding is irregular, and the thickness of individual beds ranges from less than an inch to many tens of feet. Current features and graded beds are rare. Most of these sedimentary rocks have more than 10 percent matrix, consisting of chlorite and mica, and varieties classed as arkosic, feldspathic, and lithic graywacke are all widespread. Angular monomineralic grains are predominantly feldspar and quartz; the quartz/feldspar ratio, although widely variable, averages slightly less than 1/1. Sodic plagioclase is the dominant feldspar, and over extensive areas plagioclase is the only feldspar present. In some areas, however, K-feldspar is common and may exceed 15 percent locally. Lithic fragments may comprise over half the rock; generally they are greenstone and chert, but may be shale or schist. Cement is normally a fine-grained paste of micaceous minerals and rock flour, but uncommonly is calcite or silica. The predominant chemical characteristics of the graywacke are: $K_2O/Na_2O < 1$, $Fe_2O_3/FeO < 1$, and combined water (H_2O+) > 2 percent. The physical features indicate rapid deposition of unsorted material, presumably by turbidity or fluxoturbidity currents. The mineralogic and chemical features indicate derivation of the non-K-feldspar-bearing portion from a metamorphic terrane, and the K-feldspar-bearing portion from a granitic and metamorphic terrane, with minimal chemical weathering.

The shale and siltstone accompanying graywacke are dark gray to black in color, and are essentially micro-graywacke with only a small amount of clay minerals. Like the graywacke, they have a K_2O/Na_2O ratio close to 1 and a Fe_2O_3/FeO ratio appreciably less than 1.

Conglomerate, although minor, is widespread as small lenses. Nearly all varieties include pebbles and cobbles of extraformational origin, but south of Sebastopol most conglomerates contain abundant pebbles of possible intraformational origin, as well as occasional pebbles of granite. Glaucophane schist pebbles are rare and are regarded as evidence of intraformational origin.

Limestone, largely of chemical origin, occurs sporadically along a narrow belt extending from near Gilroy to Garberville. It is economically important as a source rock for cement and geologically important as the source of diagnastic fossils. A variety colored red by goethite is associated with volcanic rocks and was precipitated in deep water through heating and agitation by submarine eruptions. A thicker white variety is also associated with volcanic rocks, and locally contains abundant pellets, oöliths, and fossil detritus that suggest a shallower environment.

Altered mafic volcanic rocks, termed greenstones, comprise about a tenth of the assemblage and are widespread. Most consist of pillows, tuffs, or breccias resulting from submarine eruptions, but some massive units may be intrusive. The volcanic accumulations range in size from a few feet to many thousands of feet in thickness and 20 miles in extent. Plagioclase and augite are the chief minerals, and olivine is rare. Altered mafic glass is a nearly ubiquitous component. Plagioclase ranges from bytownite or labradorite to albite; pyroxenes are augite, subcalcic augite, pigeonite, or titanaugite. Some pillow lavas contain pumpellyite. The least hydrous massive varieties, which are the least altered, are chemically similar to tholeiitic basalt, but with soda intermediate between spilite and tholeiite. However, most greenstones are abnormally hydrous, and their composition has been altered through reaction with sea water. As pillows and matrices provide samples of a single magma that have had different opportunities for sea water reaction, analyses of the core, rim, and matrix for two pillows were obtained. If magnesia is regarded as a constant, these analyses show from the center outward large losses in silica, alumina, lime, and soda, and smaller losses of iron; only potash was enriched in the shell or matrix. Pillow structure probably results from jet eruptions beneath the ocean, with the pillows forming by solidification of a shell around large drops of magma that result from the breaking up of the jet of magma. The concentration of soda in the core and potash in the rim may be due to reciprocal alkali transfer resulting from unusually steep thermal gradients caused by marginal cooling. After accumulation on the sea floor, reheating of the chilled borders of the pillows, due to equalization of heat in the pile of pillows, gives rise to characteristic plumose and variolitic textures by promoting crystallization in the glass.

Keratophyre, or quartz-keratophyre, occurs in several areas mapped as Franciscan. However, because they everywhere occur either as intrusions into Franciscan rocks or along tectonic zones between Franciscan and younger rocks, their inclusion as a part of the Franciscan may not be warranted.

Chert and a distinctive shale occurring with it are quantitatively minor; however, as they are believed to be chemical precipitates formed by the reaction of magma and sea water under considerable hydrostatic pressure, they are important as indicators of the oceanic depth in which part of the Franciscan was deposited. Rhythmically interlayered red or green chert and shale form lenses less than 50 feet thick and less than a mile in extent, generally with and above greenstones. The thin beds of chert within each chert-shale lens are discontinuous and terminate abruptly; they have a fairly constant thickness of an inch or two regardless of their position in the lenses. Individual beds of chert or colored shale are not interdigitated with Franciscan graywacke or the black shale that accompanies it. The chert consists of quartz or chalcedonic quartz colored by goethite or hematite and contains no clastic grains of quartz or feldspar. Radiolaria may be abundant or virtually absent. The silica content ranges from 93 to 97 percent, and the impurities are alumina or ferric iron, representing an admixture of the material of the shale parting layers. These layers consist of goethite, or locally hematite, mica, and quartz, but shreds of volcanic glass may also be present. The shale accompanying chert differs from the normal Franciscan black shale in having a K_2O/Na_2O ratio of about 10 instead of 1, and both more iron and a larger Fe_2O_3/FeO ratio. It differs from deep sea "red clay" in that the K_2O/Na_2O ratio is much larger.

The association of chert-shale lenses with greenstone suggests a genetic relation. The lenses may represent silica, alumina, and iron released by submarine volcanic rocks at the time of volcanic eruption, the eruption occurring at a depth great enough for sea water at the reactive interface to be heated to a temperature of about 350°C without boiling. At this temperature and at a pressure equal to that of oceanic depths of 13,000 feet, water can dissolve over 1,000 ppm of silica. Such heated, silica-enriched water would rise, be cooled, and quickly become oversaturated with respect to silica. Silica would then be polymerized and precipitated as a gel, apparently along with aluminum and ferrous hydroxide, and it would rain down onto the sea floor forming a mass of impure silica gel. Subsequently, by a process of diffusion and crystallization, layers that superficially resemble normal sedimentary beds would form. Similar though smaller layers were formed experimentally by Davis using sodium silicate and powdered Franciscan shale. This postulated origin for the chert-shale lenses seems to be the only one compatible with all their unusual structural and chemical features, and it implies that deposition of some Franciscan rocks must have been at a depth nearly equivalent to or greater than the average of the Pacific Ocean.

Ultramafic rock, chiefly serpentinite, constitutes a widespread part of the eugeosynclinal assemblage, and it is of economic importance as the host rock for deposits of chromite, magnesite, and asbestos, and for many mercury deposits; but this rock also causes serious engineering problems because some kinds of it are weak and subject to sliding. Most masses are tabular parallel to the general bedding of the rocks they intrude, though this does not imply intrusion when the beds were horizontal. The largest sill-like mass is 70 miles long and has an outcrop width of several miles; it generally separates Franciscan rocks in the northern Coast Ranges from miogeosynclinal rocks of the Great Valley. The highly sheared condition and lack of

peripheral metamorphism suggests that the sills were emplaced as serpentine, rather than as ultramafic magma. Several pluglike masses also intrude the Franciscan rocks and these differ from the tabular masses in being less serpentinized and by including considerable dunite in contrast to a preponderance of peridotite in the tabular masses. Chemical analyses of fresh and serpentinized ultramafic rocks, and of chromite from them, indicate they belong to the alpine type.

The assemblage of Franciscan rocks, though dominantly unmetamorphosed, includes metamorphic rocks of the zeolite, blueschist, and eclogite facies, and rarer rocks altered by metasomatism. Laumontite is the typical new mineral in zeolite facies rocks. Glaucophane, lawsonite, jadeite, stilpnomelane, pumpellyite, aragonite, and other minerals less diagnostic of the metamorphic environment occur in the blueschists. In spite of the prevalence of Na-minerals, most blueschists are neither soda-rich nor enriched in soda. The blueschists have three principal modes of occurrence. In one mode metamorphic rocks with either glaucophane or jadeite occur in small isolated patches within, and grade into, unaltered graywacke, shale, or greenstone. Some of these metamorphosed rocks are in contact with serpentine, but many others are not. In a second mode of occurrence, clearly unrelated to serpentine, similar metamorphic rocks occupy areas that are several miles wide and tens of miles long, locally indicating a limited form of regional or load metamorphism. The third mode of occurrence, which is both the most curious and widespread, is as isolated rounded masses of schist ranging from a few feet to a few hundred feet in diameter and generally surrounded by nonmetamorphosed rock. Although all the kinds of metamorphic rocks occur as isolated masses, the most common are eclogites and glaucophane-eclogites, which are known only in this latter type of occurrence. Such blocks occur in serpentine, in shear zones, and amid unaltered Franciscan rocks; they probably are tectonic inclusions.

Considerations of the probable pressure-temperature field of formation of the blueschists indicate that pressures were abnormally high ($>$5Kb) relative to the temperature ($<$300°C). If the metamorphism of the broader areas is due to load, the rocks must have reached a depth of about 70,000 feet, through downwarping and accumulation, so rapidly that a normal thermal gradient was not established. In addition they must have been uplifted soon after their depression and metamorphism, so as to prohibit the establishment of a normal thermal gradient that would have raised the temperature sufficiently to convert the blueschists to greenschist or a higher grade facies.

Fossils are rare in rocks of Franciscan lithology, but at least 25 localities have yielded fossils diagnostic of age. These indicate a span in age from Late Jurassic (Tithonian) to at least Late Cretaceous (Turonian). Most of the older fossils are from rocks east of the Hayward fault, or an extension of this fault drawn from Berkeley to Eureka, and all of the Late Cretaceous fossils are from areas west of this line.

The fossil evidence indicates the Franciscan rocks are, at least in part, age equivalents of a better known miogeosynclinal assemblage which we refer to as the Great Valley sequence as it is best exposed on the west edge of the valley, although it also extends farther west into the Coast Ranges. The Great Valley sequence, which is at least 40,000 feet thick, includes units known as Knoxville (Upper Jurassic), Paskenta and Horsetown (Lower Cretaceous), and Chico (Upper Cretaceous), and many other names have been applied locally. The miogeosynclinal Great Valley sequence differs from the eugeosynclinal Franciscan by having: no greenstone or chert, except in its basal part; a higher proportion of mudstone and shale; more uniform and thinly bedded sandstone beds; a greater percentage of conglomerate; many more fossils; and much less structural deformity.

The K-feldspar content of graywacke of both the Franciscan and Great Valley assemblages was studied. The median K-feldspar content of units of the Great Valley sequence is: Upper Jurassic (Knoxville), 0.5 percent; Lower Cretaceous, 1.1 percent; and Upper Cretaceous, 13 percent. The median values for different areas of Franciscan rocks are: east of the San Andreas and Hayward (extended) faults, 0 percent; Bay area, west of the Hayward fault and north to Cazadero, 0 percent; coastal belt, west of the extended Hayward fault and north of Cazadero, 4.5 percent; and west of the Nacimiento fault, nearly 0 percent but with many more high values than for the first two areas listed.

The increase of K-feldspar with decrease in age reflects progressive unroofing of the Late Jurassic to mid-Cretaceous Klamath Mountain and Sierra Nevada batholiths in the major source area, and thus the content of K-feldspar provides an indication of approximate age. However, because of the possibility of other sources for the sediments, the absence of K-feldspar is not an infallible indication of a pre-Late Jurassic age in the Coast Range rocks.

The specific gravity of the Franciscan graywacke differs from that of the units of the Great Valley sequence. The median values for these units are: Upper Jurassic (Knoxville), 2.59; Lower Cretaceous, 2.57; and Upper Cretaceous, 2.55. The median values for different areas of Franciscan rocks are: east of the San Andreas fault and the Hayward fault (extended), 2.65; Bay area, west of the Hayward fault and north to Cazadero, 2.65; coastal belt, west of the extended Hayward fault and north of Cazadero, 2.60; and west of the Nacimiento fault, 2.62. Values greater than 2.68 were obtained only in Franciscan rocks, and values greater than 2.70 were obtained only from graywackes that were found to be metamorphosed.

The Franciscan rocks east of the San Andreas and Hayward (extended) faults are known from fossils to include rocks equivalent in age to the Knoxville Formation (Tithonian) and lower Cretaceous strata of the Great Valley, but they also probably include pre-Knoxville rocks of post-Galice or Mariposa (Kimmeridgian) age. This is indicated by the structural position of the Franciscan beneath the Knoxville. Also the Franciscan unit is likely to represent the large amount of debris stripped from the Klamath Mountains and Sierra Nevada during the earliest part of the Nevadan orogeny. The Franciscan rocks between the San Andreas and Hayward faults in the Bay area are of Cretaceous age, and their low content of K-feldspar suggests they were derived dominantly from pre-existing Franciscan rocks.

The basement for the Franciscan is not exposed, but as the inclusions brought up in the ultramafic masses are all Franciscan rock types, the Franciscan probably was deposited directly on a basaltic crust or on peridotite. The problem of the basement of the Franciscan has not been clarified by geophysical work.

Although the Franciscan is pervasively deformed by folds and faults, the structures within it cannot generally be ascertained because of its persistent heterogeneity and lack of key beds. Most folds trend northwest, but arcuate map patterns around plunging folds are rarely obtained, probably because of widespread faulting along, and parallel to, the axial parts of the folds. The major faults, which have a similar trend, are shear zones that in places are as much as a mile wide. These contain large blocks of more resistant Franciscan rocks in a sheared matrix, and include tectonic inclusions of schist and sheared masses of serpentine. Because of their physical properties, the recognition of shear zones is of utmost importance in planning for construction projects.

The larger structural features of the Coast Ranges, which determine the distribution of the major lithic units, include other rocks in addition to the Franciscan Formation and, consequently, are better known than structures within the Franciscan. Two types of structural terranes are recognized: one has a crystalline basement like the metamorphic and plutonic rocks of the Klamath Mountains and Sierra Nevada; the other, which includes all the Franciscan rocks, rests on a basement that is unknown but that probably is basaltic substratum or peridotite. On the crystalline basement the sedimentary strata are relatively thin, broadly folded, and cut by few faults; on the other basement the sedimentary rocks are thick, more highly deformed, and more faulted. The terranes with these two different basements are, so far as known, separated by major faults.

The fault that separates the Franciscan rocks of the northern Coast Ranges from the crystalline rocks of the Klamath Mountains and Sierra Nevada extends south from the Oregon border to the northern end of the serpentine mass that lies between the Franciscan rocks and the miogeosynclinal rocks of the Great Valley. South of this point the separation between the crystalline basement and unknown basement continues, beneath the miogeosynclinal cover, along the great magnetic high that trends the length of the Great Valley.

The western limit of this area of rocks with unknown basement is the San Andreas fault, which trends northward through the Coast Ranges and joins the Mendocino Escarpment fault zone. West of the San Andreas fault zone is a crystalline block with granitic plutons and with no known sedimentary strata of Late Jurassic to Late Cretaceous (pre-Campanian) age. This block, which is only 40 miles wide but 300 miles long, is bounded on the west by the Nacimiento fault. To the west of the Nacimiento fault is another terrane of rocks with unknown basement in which the eugeosynclinal Franciscan rocks are largely covered by younger rocks or by the Pacific Ocean.

Other major structures pertinent to an understanding of the distribution of the Franciscan rocks are within the terrane lying east of the San Andreas fault. The Hayward fault, which diverges eastward from the San Andreas fault, is more important than has hitherto been recognized. In a general way, it divides the Franciscan into two parts, with the Franciscan rocks to the east being Late Jurassic to Early Cretaceous in age and those to the west being younger and including rocks that are Late Cretaceous in age. Also, it sharply separates Late Cretaceous Franciscan rocks on the west from Late Cretaceous strata of the Great Valley sequence on the east.

East of the Hayward fault the rocks appear to be broadly arched to form the Diablo antiform. In the Diablo Range the axial portion of the antiform is unmistakable, as it is the site of several piercements; north of San Francisco Bay the antiform is less well defined, and north of Clear Lake its position is uncertain.

The recognition of: (1) the post-Knoxville age for part of the Franciscan rocks, (2) the Late Cretaceous age for the granite between the San Andreas and Nacimiento faults, and (3) the significance of the K-feldspar content in the graywackes, clearly defines many problems pertaining to the distribution of the Franciscan rocks and coeval strata of the Great Valley sequence. Previous considerations of Franciscan rocks grading upward to Knoxville rocks or grading laterally into Knoxville or other strata of the Great Valley sequence must be modified, and apparently the modification must include major tectonic dislocation. Several mechanisms that might account for the major dislocations are large strike-slip movement, rifting and westward drifting of the entire Coast Ranges, and thrust faulting or gravity sliding. However, none of the mechanisms discussed will alone completely explain the data now available, although some combination of these dislocations may provide a satisfactory solution.

Part I - Description of the Franciscan

INTRODUCTION

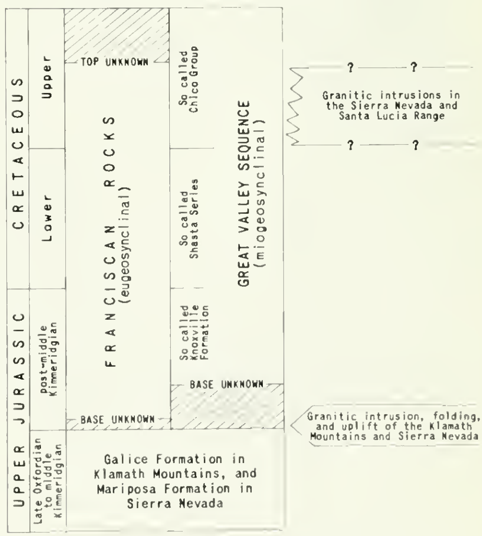
A heterogeneous assemblage of graywacke, shale, altered volcanic rocks, chert, limestone, and peculiar metamorphic rocks found on the San Francisco peninsula has long been variously referred to as the Franciscan Series, Franciscan Group, or Franciscan Formation. Although no specific type locality has been designated, the San Francisco peninsula has been generally accepted as the type area. Rocks of similar lithology which form the "basement" for much of the California Coast Ranges from the Oregon border southward to near Santa Barbara also have been generally designated as belonging to the Franciscan Formation, on the basis of gross similarity in lithology with the rocks of the San Francisco peninsula (pl. 1). Metamorphic rocks exposed still farther south, in the Palos Verdes Hills and on Santa Catalina Island, have also been correlated with the type area and regarded as metamorphic equivalents of the Franciscan, though they have been named the Catalina Schist.

Throughout the entire extent of the Franciscan few fossils have been found, and since neither the stratigraphic base nor top of the unit has been recognized, the age of the rocks has long been a matter of controversy. On the basis of broad regional relations to other major lithologic units, the Franciscan for many years was regarded as probably of post-Paleozoic and pre-Late Jurassic (Knoxville) age. Later work by Diller (1907), Louderback (1905), and Taliaferro (1942), established that the Franciscan is probably younger than the Galice and Mariposa Formations of Kimmeridgian age, and Taliaferro (1943) suggested that the upper part of the Franciscan is, in part, equivalent to and gradational into the lower beds of the Knoxville. In recent years, fossils of Early and Late Cretaceous ages have been found in several areas in rocks referred to as Franciscan, and it has become apparent that the term "Franciscan" has been applied to rocks of widely different ages whose deposition was not necessarily continuous nor confined to one depositional trough (fig. 1). Thus "Franciscan" is not being used by most geologists as a group or formational designation in the accepted meanings of these terms; instead, it is being used to designate a particular lithologic assemblage, in much the same connotation as the European term "Flysch." We believe that most useful terminology would be to refer to all these eugeosynclinal rocks informally as the "Franciscan assemblage," reserving the term "Franciscan Formation" for the rocks at the type locality and any others that can be positively correlated with them. This assemblage would include rocks that are "representative of a particular sedimentary and *tectonic* environment" (Silberling and Roberts, 1963, p. 6). As "assemblage" used in this sense is conceptual and interpretive it cannot be misconstrued to be a rock-stratigraphic term, like formation or group; however, the Stratigraphic Code makes no provision for this kind of terminology. Because of this we do not herein use "Franciscan assemblage," but we have tried to restrict our use of Franciscan Formation to apply only to the rocks of the type locality and others that are clearly correlative with them.

As typically developed, the assemblage of rocks generally referred to as Franciscan by California geologists comprises thick graywacke sequences containing minor interbeds of dark shale, interlayered mafic volcanic rocks of submarine extrusive origin, chert that is closely related to the extrusives, limestone that is chiefly a chemical precipitate, and unusual metamorphic rocks containing minerals such as glaucophane, jadeite, lawsonite, pumpellyite, and stilpnomelane. In addition, ultramafic rocks, largely serpentinites, are an integral part of the eugeosynclinal assemblage, although geologists have generally excluded them from the Franciscan Formation because the ultramafic rocks are intrusive.

The Franciscan has other unusual aspects in addition to the character of its rocks. Its base has not been observed, and what lies beneath it is unknown. Likewise, the upper limit has not been precisely defined.

Figure 1 (below). Generalized correlation chart showing age relations between Franciscan rocks, Great Valley sequence, and Galice and Mariposa Formations, and granitic rocks of the Klamath Mountains, Sierra Nevada, and Santa Lucia Range.



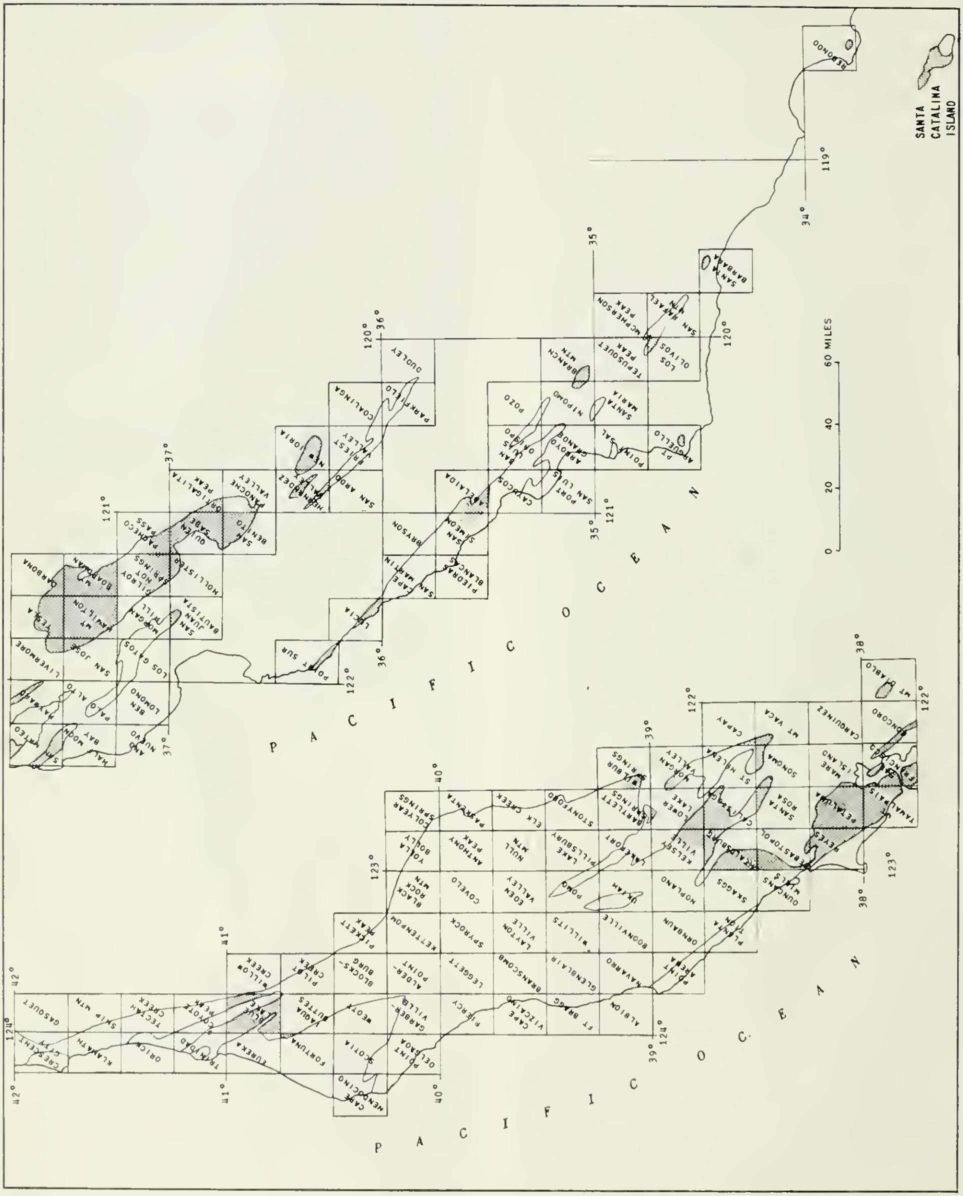


Figure 2. Index map showing 15-minute quadrangles in which Franciscan rocks are exposed. Areas of Franciscan exposures are outlined, and are shaded where geologic maps at a scale of 1:62,500 or larger are published or available in theses.

Locally Franciscan rocks appear to be overlain by non-Franciscan rocks of Late Jurassic age, but in other areas the Franciscan is clearly of Late Cretaceous age. Within the Franciscan, correlation of isolated outcrops cannot be made, because distinctive sequences or key beds, with the probable exception of rare foraminiferal limestones, have not been recognized. Structures are generally so complex and fossils so rare that the stratigraphic succession of the whole assemblage has not been established. Better understanding of the Franciscan is also prevented by the lack of adequate geologic mapping, as perhaps only one-tenth of the thousands of square miles of outcrop area has been mapped adequately at scales of 1:62,500 or larger (see fig. 2).

The Franciscan rocks are bordered on the east, along the western edge of the Great Valley, by an enormously thick sequence of coeval clastic rocks ranging in age from Late Jurassic to Late Cretaceous (fig. 3). This sequence, which comprises at least 40,000 feet of sandstone, shale, and conglomerate, is informally referred to in this report as the Great Valley sequence. It differs from the eugeosynclinal assemblage comprising the Franciscan chiefly in its paucity of volcanic rocks and, for this reason, is referred to as miogeosynclinal.[1] It also is structurally less deformed, much more fossiliferous, and more regularly bedded than are the Franciscan rocks.

These and other differences generally allow one to assign, with confidence, a group of rocks to either the Franciscan or Great Valley sequence. Rocks in some areas, however, have intermediate characteristics which necessitate a rather arbitrary decision as to assignment to one or the other of these assemblages. One problem area is the "coastal belt" of Bailey and Irwin (1959). This belt contains medium-grained, massively bedded graywackes, with minor amounts of shale and conglomerate, all structurally deformed in such a fashion that they closely resemble the rocks typical of the Franciscan Formation. However, the belt contains only a little greenstone, chert, serpentine, and blueschist-grade metamorphic rock. For descriptive purposes the sedimentary rocks of this belt are included with the Franciscan in this report, though it is likely that when sufficient work has been done, these rocks will prove to be distinctive enough to stand as an independent stratigraphic unit.

Another group of rocks whose assignment is controversial is found in the few places where volcanic rocks and chert occur in the Upper Jurassic Knoxville Formation. Sedimentary rocks associated with these volcanics are mainly fossiliferous shale similar to the nonvolcanic miogeosynclinal part of the Knoxville. Although there is some merit in treating these volcanic-bearing sequences as a hybrid Franciscan-Knoxville Group, as did Taliaferro (1943a), it seems to us that their dominant lithologic and structural features are more like those of the Great Valley sequence than like the Franciscan Formation. For descriptive purposes, we have therefore excluded them from the Franciscan in our discussion of its lithology and in the maps included with this report.

The assemblage of Franciscan rocks is characterized by great diversity, and because of this, as well as its great expanse, no single geologist has been able to gain intimate knowledge of its many aspects in all areas. One of our main purposes in preparing this article is to integrate descriptive data now available in published reports and unpublished theses, and to supplement this, where possible, with whatever additional data we could gather readily. More study is needed before the several different lithic types can be precisely described or limits placed on their variations, and we hope to encourage such study by pointing out the inadequacies of the available data. Another objective of this report is to determine the significance of the various lithologies in terms of environment or mode of formation. These topics, which deal chiefly with internal aspects of the Franciscan, are treated in part 1 of this report.

In part 2 we discuss the relation of the Franciscan rocks to the other rocks of western California and the significance of the assemblage in the geology of the Coast Ranges. Until the record of the Franciscan rocks from their deposition to their present folded, faulted, and locally metamorphosed condition is understood, and until their peculiar juxtaposition against coeval rocks of a different facies is explained, the geologic history of the Coast Ranges will remain obscure. Some ideas regarding the late Mesozoic paleogeography and subsequent orogenic dislocations are offered, but it seems likely that a complete understanding of the geologic history will not be obtained until the assemblage of Franciscan rocks is broken down into smaller recognizable formational units and their ages and distributions determined. We have suggested, in this report and elsewhere (Bailey and Irwin, 1959), some criteria whereby parts of the assemblage can be differentiated, and we believe that application of these techniques, and others yet to be discovered, should lead to a far clearer picture of the history of the Coast Ranges than we now possess.

ACKNOWLEDGMENTS

In this report, which incorporates the work of many geologists, we have attempted to acknowledge fully the specific sources of data, either published or unpublished, at appropriate places in the text and on the maps. We are equally grateful for the helpful suggestions received from the many geologists with whom we have discussed the Franciscan during preparation

[1]Although the presence or absence of volcanic rock is the chief basis for referring to the Franciscan Formation and Great Valley sequence as eugeosynclinal and miogeosynclinal, respectively, they have other differences that are summarized in table 18, p. 124. We recognize that our use of the term "miogeosynclinal" does not conform to the use of some American geologists, but our use does conform to the original intent of Stille who coined the term (see Knopf, 1960).

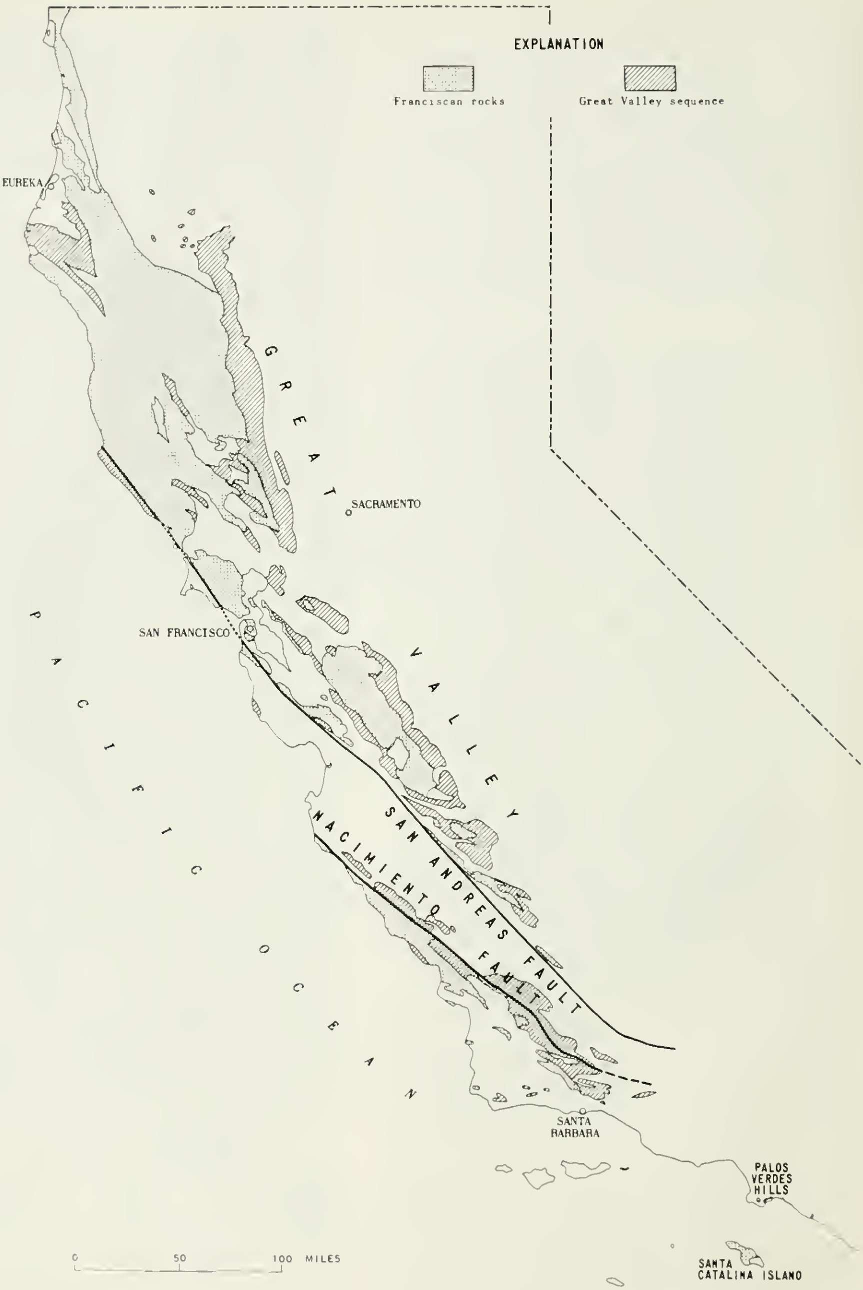


Figure 3. Generalized map showing distribution of Franciscan rocks and Great Valley sequence.

of this report, though they are so numerous that they cannot be mentioned individually. The section on metamorphic rocks was read by R. G. Coleman, A. O. Woodford, and W. G. Ernst, and their constructive criticisms are appreciated. Chemical analyses of some of the metamorphic rocks were obtained from Coleman, and other analyses of rocks in the San Francisco area were obtained from Julius Schlocker, who also furnished X-ray data on the fine fractions of the graywacke.

Of the hundreds of graywacke samples used in determining K-feldspar distribution and specific gravity, about 10 percent were loaned to us by other geologists. These geologists and the respective sample localities are: James Berkland, northern San Francisco Bay area; Manuel Bonilla, San Francisco South quadrangle; Stewart Chuber, Elk Creek and Fruto quadrangles; Ivan Colburn, Mount Diablo area; T. W. Dibblee, Jr., Black Mountain area of the Palo Alto quadrangle; D. H. Radbruch, Oakland East quadrangle; Fred Schilling, Pacheco Pass quadrangle; Julius Schlocker, San Francisco North quadrangle and northern San Francisco Bay area; and Clyde Wahrhaftig, Mount Tamalpais quadrangle.

HISTORICAL SUMMARY

Early Reconnaissance (1858-1894)

The history of the study of the Franciscan goes back to the earliest days of geologic exploration in California, and the literature treating various aspects of its diverse lithology, mineralogy, and associated mineral deposits is voluminous. No attempt is made here to repeat all the ideas that have been expressed or to cite every reference, but rather we will give a résumé of the main course of development of thinking concerning the broader aspects of the Franciscan—its lithologic character and depositional environment, its age, its relation to other rocks, and its role in the geologic history of the Coast Ranges. For a more detailed discussion, particularly of the early work and the unusual metamorphic rocks, the reader is directed to the excellent summary by Taliaferro (1943a, p. 112-122).

Blake (1858) first described the rocks in the vicinity of San Francisco Bay that subsequently were designated the Franciscan Series. He grouped all of the sedimentary rocks of the Bay area into one unit which he called the San Francisco or California Sandstone. This unit was tentatively assigned to the Tertiary on the basis of an echinoid *Scutella interlineata*, but Blake suspected that Cretaceous beds might also be present. Blake also mentioned most of the other characteristic Franciscan rock types; the volcanic rocks were referred to as "Trappean" rocks, chert was regarded as a metamorphic rock, and the serpentine he described as an intrusive rock younger than the sandstone.

In 1865, Whitney recognized the presence of rocks of several different ages in the vicinity of San Francisco, and he restricted the name "San Francisco Sandstone" to rocks thought to be of Cretaceous age. This age determination was based on a single specimen of *Inoceramus* obtained from Alcatraz Island and described as *I. ellioti* by Gabb (1864). In the Mount Diablo area, Whitney believed that he could demonstrate the alteration of normal Cretaceous shales to thin-bedded chert, which he referred to as jasper, and he also thought that the mafic igneous rocks and serpentine were of metamorphic origin.

By 1885, a considerable number of reconnaissance studies had been carried out in the Coast Ranges. A leader in this work was Becker (1885) who believed that much of the sequence characterized by chert, serpentine, and other distinctive rock types, now ascribed to the Franciscan, was metamorphosed, and that the *Buchia* [*Aucella*[1]]-bearing beds, which he called the Knoxville Series, graded into this metamorphic series. These Knoxville beds were correlated with his Mariposa Beds of the Sierra foothills and assigned a Neocomian (earliest Cretaceous) age.

In 1886, Becker further amplified his view of Coast Range geology by stating that the entire area from New Idria north to Clear Lake was underlain by granite of very uniform character, and that the great mass of overlying sedimentary rock was derived from this granite, but was altered by regional metamorphism of irregular intensity. The supposed presence of the granitic basement was based mainly on the feldspathic nature of the sandstone, as no contact of the basement rocks and the overlying sedimentary rocks was found. Becker recognized various types of metamorphic alteration, whereby shales were thought to have been converted to glaucophane schists in some areas but were thought to have formed phthanites (cherts) in other areas. The presence of organic remains was noted in the chert, but the significance of the radiolarian tests was not appreciated. Serpentine was thought to have been derived mainly from sandstone or from an intermediate granular metamorphic rock; only a small amount of serpentine was thought to have formed from an olivine-rich igneous rock. The altered sedimentary rocks were thought to be no older than Neocomian, and metamorphism supposedly occurred at the end of this stage.

Fairbanks, in a series of papers from 1892 to 1895, strongly attacked Becker's idea concerning the age of the Franciscan rocks. Although Fairbanks supported Becker's conclusion regarding the metamophic nature of the Franciscan, he believed the rocks to be of pre-Cretaceous age and separated from the *Buchia*-bearing Knoxville beds by a pronounced unconformity. At that time, all of the Knoxville was considered to be earliest Cretaceous, as Upper Jurassic fossils were not definitely recognized until some years later. In 1895 Fairbanks introduced the name "Golden Gate Series" for those rocks now called Franciscan, and the age of this series he considered to be Late Jurassic, about

[1] The name "*Buchia*," instead of its synonym *Aucella*, is used throughout this report except in quotations.

GEORGE F. BECKER. George Becker was an instructor in mining and metallurgy at the University of California at Berkeley and later was a geologist with the U.S. Geological Survey from 1879 to 1919. From 1883 to 1886 he made detailed studies in mining districts in the Coast Ranges, which were published as USGS Monograph 13, "Geology of the quicksilver deposits of the Pacific Coast." One of the main contributions of this report was the publication of chemical analyses of minerals, rocks, and spring waters made by W. H. Melville. Becker believed that rocks of the Franciscan were regionally metamorphosed, and that locally they graded into unmetamorphosed Knoxville beds. *(U.S. Geological Survey Portrait 87, George F. Becker, 1910.)*

HAROLD WELLMAN FAIRBANKS. H. W. Fairbanks came to the University of California at Berkeley, having previously obtained a B.S. from the University of Michigan in 1890. He studied under A. C. Lawson, and received his Ph.D. in 1896 after having submitted a series of geological papers in fulfillment of the thesis requirement. From 1890 to 1895 he traveled widely throughout California as a Field Assistant for the California State Mining Bureau and prepared hundreds of pages of reports on specific counties from San Diego County to Shasta County. In 1894 he described the "uncrystalline rocks" of the Coast Ranges, and in 1895 he wrote of these rocks (Fairbanks, 1895, p. 416), "For this collection of strata, consisting chiefly of jasper, sandstone, shale, and slate, typically developed about the entrance to San Francisco Bay, *the designation of Golden Gate series is proposed.*" From 1897 to 1899 he mapped for the U.S. Geological Survey an extensive area of his "Golden Gate series" rocks near San Luis Obispo, but in describing these in the San Luis folio he was forced to refer to them as the "San Luis formation of the Franciscan group." By 1907, after publishing about 50 geologic reports and abstracts, he returned to an earlier interest in geography and teaching, essentially giving up geologic research. He subsequently taught geography at the University of California and the University of Southern California, published several geography text-books, and traveled widely throughout the world. *(Photo courtesy of University of Michigan Alumni Association.)*

ANDREW COWPER LAWSON. "Andy" Lawson was a distinguished Professor of Geology at the University of California at Berkeley from 1890 to 1952. Soon after his arrival at the University he began one of the first formal courses in Field Geology in the United States, with the field mapping being concentrated in the San Francisco Bay area. As a result of this work Lawson in 1895 named the heterogeneous assemblage of rocks found on the San Francisco Peninsula the "Franciscan Series," and in 1914 published the well known San Francisco folio. Following the 1906 earthquake, caused by movement along the San Andreas fault, he served as Chairman of the State Earthquake Investigation Commission, and in 1907 edited the reports of many geologists to form volume 1 of the classic study published by the Carnegie Institution of Washington. He also taught and inspired many other geologists who have contributed to the understanding of the Franciscan Formation, among whom are Charles Palache, F. L. Ransome, H. W. Fairbanks, Adolph Knopf, E. F. Davis, and N. L. Taliaferro. *(Photo from the files of the Geological Society of America.)*

ELMER FRED DAVIS. "Fritz" Davis studied as an undergraduate and graduate under A. C. Lawson and G. D. Louderback at the University of California at Berkeley, receiving his Ph.D. in 1917. His Doctoral thesis, which dealt with the petrography and origin of the Franciscan chert, and to a lesser extent with the associated sandstones, led to the publication of two reports (Davis, 1918, a,b), which still are the most exhaustive studies of the Franciscan chert and sandstone. While engaged in graduate work at the University he served as Instructor in Geology and was also in charge of the seismographic station, which resulted in his publishing the Berkeley and Lick Observatory records as nos. 4-18 (1913-20) of the University of California Seismological Station Bulletin. He left the University in 1919 to work for the Shell Co., where he became Chief Geologist and later Vice President for the Pacific Coast Area from 1929 to 1948. Since 1948 he has been a consulting geologist, and currently he is a consultant and director of the Home Oil Co. of Canada.

NICHOLAS LLOYD TALIAFERRO. "Tucky" Taliaferro (pronounced "Toliver") studied under Lawson at Berkeley, where he received his A.B. and Ph.D. degrees. He joined the faculty at Berkeley in 1926, and continued in this capacity until his untimely death in an automobile accident in 1961. For many years he was in charge of the popular field course, in which students mapped extensive parts of the central and southern Coast Ranges. Many advanced students introduced to the Franciscan rocks in this summer field work selected Coast Range quadrangles for Ph.D. thesis study, and a large proportion of the published reports on Coast Range quadrangles have thus resulted from Taliaferro's leadership. Taliaferro's best known publications are the "Franciscan-Knoxville problem" published by the A.A.P.G., and a summary report on the geology of the Coast Ranges contained in Bull. 118 of the Calif. State Division of Mines. *(Photo from the files of the Geological Society of America.)*

PHOTO 1. GEORGE F. BECKER
1847-1919

PHOTO 2. HAROLD WELLMAN FAIRBANKS
1860-1952

PHOTO 3. ANDREW COWPER LAWSON
1861-1952

PHOTO 4. ELMER FRED DAVIS
1887-........

PHOTO 5. NICHOLAS LLOYD TALIAFERRO
1890-1961

"at a horizon which corresponds closely to that represented by the Mariposa beds" (Fairbanks, 1895, p. 426). He believed that the Golden Gate Series had been deposited on an eroded surface developed on ancient crystalline rocks which predated the granitic rocks of the Sierra Nevada. Intrusion of serpentine was thought to be post-Knoxville, probably mid-Cretaceous, as both Franciscan and Knoxville rocks were intruded by large masses of serpentine. Fairbanks (1894) believed that the typical Franciscan chert was a product of organic activity rather than a result of metamorphism, and this conclusion was substantiated in the same year by Hinde (1894) who described Radiolaria in chert obtained from Angel Island in San Francisco Bay.

Definitive Studies, Chiefly in San Francisco Area (1894-1920)

Beginning in the early 1890's, intensive studies of Franciscan rocks were undertaken by various members of the Department of Geological Sciences of the University of California at Berkeley. Ransome (1894) and Palache (1894a) clearly showed that serpentine was formed by the alteration of ultramafic igneous rocks, rather than by the metamorphism of sandstone. Ransome also proposed that glaucophane schist and related rocks were formed by contact metamorphism along the margins of serpentine bodies.

Lawson (1895) named as the Franciscan Series the rocks in the vicinity of San Francisco that had been referred to previously as San Francisco Sandstone or Golden Gate Series. His rejection of the older names was not explained, but the name Franciscan has persisted, and the older names are now abandoned. Lawson's Franciscan Series, defined without mention of a specific type section, consisted of the sedimentary and volcanic rocks of great thickness, but he excluded the associated ultramafic intrusives in the San Francisco area. The Franciscan rocks were first thought to rest on an eroded surface of the Montara Granite, but Lawson (1914) later recognized that the supposed basal conglomerate resting on his Montara was of Tertiary age and did not belong to the Franciscan Series.

The first detailed quadrangle maps of Franciscan rocks were a part of the U.S. Geological Survey San Francisco Folio by Lawson, published in 1914. In it he divided the Franciscan Group into the following five formations, listed in descending stratigraphic order: Bonita Sandstone, Ingleside Chert, Marin Sandstone, Sausalito Chert, and Cahil Sandstone. The sandstone units were described as essentially similar in appearance, so position within this sequence could only be determined with reference to the chert units which served as key beds. Later workers (Schlocker, Bonilla, and Radbruch, 1958) have found that chert occurs at several stratigraphic levels and does not form persistent beds that are continuous throughout the entire area. Moreover, Lawson failed to recognize the structural complexities which confused the order of his original sequence. Thus, Lawson's stratigraphic classification of the type Franciscan has not been found to be applicable either throughout the type area or elsewhere.

Lawson (1914) envisaged a complex series of events in order to explain the alternation of distinctive lithologies in the Franciscan. He postulated that deposition began on the sinking bottom of a transgressing sea. His Cahil Sandstone included a Calera Limestone Member that was described as a foraminiferal ooze deposited far from shore in deep water beyond the range of deposition of terrigenous material. Chert was also considered to be a deep-water, organic deposit, although in earlier papers he had argued for a shallow-water, nonorganic, chemical origin. Deposition of these organic deposits, he believed, was controlled by fluctuations of the strandline; shallow water during periods of regression permitted deposition of terrigenous sediments with resulting cessation of organic deposition. This transgressive-regressive cycle was thought to have been repeated three times, thus producing the three clastic units, two chert units, and one limestone unit. All of the Franciscan was considered to be of marine origin, with the bulk of the sediments being deposited in shallow water.

The age of the Franciscan and its relation to other formations were recognized by Lawson as presenting puzzling problems involving apparently contradictory data. He assumed that his Montara Granite in the Coast Ranges was correlative with the granitic rocks of the Sierra Nevada, which were at that time thought to be of Cretaceous age. He also thought that the Franciscan postdated the Montara Granite because of an abundance of granitic debris in the Franciscan, because of a lack of granitic intrusions into the Franciscan, and because of a lack of high-grade metamorphism in the Franciscan. Later work (Curtis, Evernden, and Lipson, 1958) has apparently confirmed the Cretaceous age of the Montara Quartz Diorite, which is the same as Lawson's Montara Granite, but the relation of this rock to the Franciscan is still obscured because of structural complexities along the San Andreas fault (see Hill and Dibblee, 1953). Lawson also concluded that the Knoxville beds rest unconformably on the Franciscan, and that as the Knoxville was regarded as of earliest Cretaceous age, the Franciscan must be pre-Cretaceous. This interpretation was obviously incompatible with a Cretaceous age for the supposed granitic basement rocks, and it led Lawson to suggest that either his Montara Granite was older than the granitic rocks of the Sierra Nevada, or that a hitherto unrecognized long interval of time separated the Jurassic and the Cretaceous periods. During this lost time interval, the granitic rocks of the Coast Ranges were intruded and eroded, the Franciscan deposited and folded, and the Knoxville was then laid down unconformably on the Franciscan during the Early Cretaceous. Neither of these ideas appearently

had much appeal, even to Lawson, and later work has shown that they cannot be seriously considered.

Davis (1918a, 1918b) wrote two reports giving excellent detailed descriptions of the Franciscan cherts and sandstones. He concluded that the radiolarian cherts are not deep water, organic ooze deposits, but instead are formed in shallow water through the action of siliceous springs associated with volcanic activity. Although he accepted a marine origin for the chert-bearing portion of the Franciscan, he thought that the bulk of the sedimentary rocks of the Franciscan were of nonmarine, fluviatile origin. Evidence for this interpretation was seen in the sandstones that contain an abundance of shale chips, thought to have formed from dried, cracked mud, and in the presence of thick conglomeratic lenses, which were considered to be of fluviatile deposition.

Broader Studies (1920-1962)

Knowledge of the Franciscan rocks was briefly summarized by Reed (1933) and Reed and Hollister (1936) who, on the basis of distribution, subdivided the Franciscan terranes into Northern Franciscan, Central Franciscan, and Southern Franciscan areas. The northern area lies entirely east of the San Andreas fault; the central area lies entirely west of the Nacimiento fault; and in the southern area the Franciscan rocks are poorly exposed as they crop out only south of the Transverse Ranges in the Palos Verdes Hills and on Santa Catalina Island. The rocks in each of these areas were thought to have been deposited in separate basins, but lithologic differences from one basin to another were not noted. Reed and Hollister (p. 1551) suggested that part of their Franciscan Stage may be as old as late Paleozoic or Triassic, but because no supporting paleontologic data was cited, this suggestion has not generally been accepted.

In 1943, N. L. Taliaferro (1943a) summarized the known data concerning the Franciscan, and suggested that, rather than being a unit of uncertain age with unknown or indefinite relations to other rocks, the Franciscan constitutes a widespread formation with narrow age limits and with well-established relations to younger and older rocks. In brief, Taliaferro believed: (1) the Franciscan was deposited on an ancient crystalline basement (Sur Series and Santa Lucia Granodiorite) of uncertain age, but possibly as old as early Paleozoic or even Precambrian; (2) deposition began after deformation of the Mariposa and Galice Formations of Kimmeridgian age, because in southern Oregon the Franciscan was found to rest unconformably on the weakly metamorphosed Galice; and (3) the contact between the Franciscan and the overlying Knoxville was gradational, not unconformable; in several places fossilliferous Knoxville shales were associated with volcanic rocks and radiolarian cherts similar to those of the Franciscan.

Taliaferro recognized four stages of development of his Franciscan-Knoxville Group, but the extent and distribution of each stage was not specified. The four stages are:

1. First stage—lower Franciscan. Mainly deposition of sandstone with little volcanism and few chemical or organic sediments.
2. Second stage—upper Franciscan. Beginning of widespread volcanic activity with maximum development of chert and foraminiferal limestone. Beginning of intrusion of mafic and ultramafic rocks accompanied locally by metamorphism.
3. Third stage—upper Franciscan and lower Knoxville. Shales become more abundant; volcanism wanes with resulting decrease in chert. Continued intrusion of ultramafic rocks and formation of schists. Shales in places abundantly fossiliferous.
4. Fourth stage—Knoxville. Deposition of shale and siltstone predominates; cessation of volcanic activity and formation of chert except in local areas. Schists developed only in a few places.

Most of the sediments of his Franciscan-Knoxville Group, he believed, were derived from a western source, as he thought that in going westward the grain size increased and the quantity of shale diminished. This idea implies contemporaneity of coarse-grained western deposits and shaly eastern deposits—a supposition which Taliaferro did not prove and which later information has indicated may be incorrect.

The age of the Franciscan was stated by Taliaferro (1943a, p. 195) to be pre-Knoxville (Tithonian). He based this mainly on field relations and on two Ichthyosaur rostra described by Camp (1942). These fossils were found in chert cobbles in stream or terrace deposits along the east side of the Diablo Range and probably were derived from the Franciscan rocks, as he suggested. Concerning the age of these fossil bones, Camp (1942, p. 370) states:

> "Ichthyosaur remains such as these provide somewhat insecure evidence upon which to base a precise age determination, as some of the Upper Jurassic forms continue into the Lower Cretaceous. So far as may now be determined, the Franciscan species franciscanus shows closest resemblances, in details of tooth structure, to *Ichthyosaurus posthumus* from the Tithonian (Portlandian) lithologic beds of Solnhofen (sic). A few other Upper Jurassic and Lower Cretaceous forms seem to be closely related as well as that form *(marathonesis)* of *(Ichthyosaurus)* '*australis*' described by Etheridge and Longman from Queensland."

Despite Camp's cautious appraisal of the age significance of these fossils, Taliaferro (1943a, p. 195) did not hesitate to state that:

> "Both the stratigraphic evidence and fossil evidence (the ichthyosaurs described by Camp and the fossils collected by the writer) agree and clearly indicate that the Franciscan may be accurately dated [as Tithonian]."

Just prior to the publication of Taliaferro's Franciscan-Knoxville paper, Thalmann (1942) reported the occurrence of Upper Cretaceous Foraminifera in Calera-like Franciscan limestone from the quarry of the Permanente Cement Co. He identified, among others, *Globotruncana* sp. aff. *G. appenninica* Renz and *G. linneiana* (d'Orbigny), which suggested an age not

Photo 6. Aerial view of northern Coast Ranges looking east from a point near Elk, 15 miles north of Pt. Arena. Entire area is underlain by Franciscan rocks. Long, north-northwesterly trending ridges, separated by valleys that probably follow faults, are typical of this part of the Coast Ranges. Pleistocene summit surfaces and terraces are prominent along the coast.

older than Turonian and not younger than Santonian. Thalmann (1943) later described Foraminifera from Franciscan limestone near Laytonville, as well as from south of Olema (Point Reyes quadrangle) and from the similar Whitsett Limestone Lentils of Diller (1898) of southern Oregon. These limestone lentils were correlated with the Calera Limestone Member and were also assigned a Turonian age. Later work by Cushman and Todd (1948), Church (1952), and Küpper (1955, 1956) resulted in a slight modification of Thalmann's age assignment, but all of these workers agreed that the foraminiferal assemblages of the Calera Limstone Member and equivalent rocks are Cretaceous and probably of mid-Cretaceous age (Albian-Turonian).

The significance of the Late Cretaceous age of the Calera Limestone Member has been controversial, as some workers (for example, Walker, 1950, p. 5) have suggested that the limestone is a younger unit that is sheared into the surrounding mass of older Franciscan rocks. However, the later finding of ammonites of Albian and Cenomanian ages (Schlocker, Bonilla, and Imlay, 1954; Hertlein, 1956) in graywacke of the type Franciscan clearly shows that the Calera Limestone Member and some of the other Franciscan rocks are approximately coeval.

Irwin (1957, 1960), during the course of reconnaissance geologic mapping of the northern Coast Ranges, found several new fossil localities which yielded *Buchia crassicollis* from rocks assigned to the Franciscan. On the basis of this and the older paleontologic data, he emphasized that the Franciscan ranges in age from Late Jurassic to Late Cretaceous and suggested that it is a volcanic-rich facies of the volcanic-poor Sacramento Valley sedimentary sequence. This con-

cept is theoretically appealing, but sufficient data were not available to demonstrate the nature of the facies transition. A further outgrowth of Irwin's reconnaissance study of the northern Coast Ranges was the recognition (Bailey and Irwin, 1959) that the K-feldspar content of much of the Franciscan of northern California differed markedly from the Late Jurassic Knoxville and the Cretaceous rocks of the Sacramento Valley sequence. The Knoxville was found to average about 0.5 percent K-feldspar, the Lower Cretaceous rocks about 2.8 percent, and the Upper Cretaceous rocks about 10.6 percent. The Franciscan rocks immediately west of the Sacramento Valley rocks in northern California, on the other hand, was found to contain generally no K-feldspar, and this striking difference between rocks of similar age seems to preclude a simple facies change. Bailey and Irwin also found that a belt of dominantly sedimentary rocks, lying west of U.S. Highway 101, had a high K-feldspar content, and they suggested excluding this belt, which they termed the "coastal belt," from the Franciscan Formation.

DISTRIBUTION OF THE FRANCISCAN

The assemblage of Franciscan rocks extends along the western margin of North America for most of the length of the State of California. By customary usage, the northern boundary of the Franciscan is the California-Oregon border, where it is exposed only in a narrow band between the Pacific Ocean and the older rocks of the Klamath Mountains province. Southward, the eastern limit is the major fault that forms the western and southern boundary of the Klamath Mountains province and extends for over 150 miles to the Great Valley of California. South of this junction, the eastern limit of Franciscan exposures follows the western border of the Great Valley to its southern end, where Franciscan rocks are largely covered by the younger rocks of the Santa Ynez Mountains of the Transverse Ranges. A more easterly extension of the Franciscan rocks beneath the mantle of miogeosynclinal sedimentary rocks in the Great Valley has been postulated chiefly on the basis of rocks recovered from a few deep drill holes. However, because the older rocks of the western Sierra Nevada Foothills are somewhat similar to the Franciscan rocks, the assignment of these cores to the Franciscan unit can be questioned.

The western margin of Franciscan exposures north of the Transverse Ranges is the Pacific shore, but, within much of the southern and part of the northern Coast Ranges, the Franciscan is strangely absent in a long corridor of metamorphic and granitic rocks that lies between the San Andreas and Nacimiento faults (see fig. 3). West and south of the Nacimiento fault, the Franciscan rocks on the mainland are covered by a mantle of younger sedimentary rocks over extensive areas, and doubtless the coastal waters of the Pacific Ocean also conceal considerable Franciscan rock.

South of the Transverse Ranges, metamorphic rocks underlying the Palos Verdes Hills on the mainland (Woodring and others, 1946) and on Santa Catalina Island (Bailey, 1941) have been described as a possible continuation of the Franciscan. According to Woodford (1960, p. 408), the widespread presence of glaucophane schist in the San Onofre Breccia of Miocene age suggests an offshore southeastern extension of the schist for at least 65 miles. Glaucophane-bearing rocks, thought to be part of the Franciscan, were sampled in place on the Sixtymile, Fortymile, and Thirtymile Banks offshore from San Diego (Emery, 1960, p. 66). Further southward, rocks that may be correlative with the Franciscan have been described (Hanna, 1925, 1927; Beal, 1948; van West, 1958) at several places, chiefly on islands along the southern half of the west coast of Baja California.

In southern Oregon, the extension of rocks mapped as Franciscan in California was assigned by Wells and Peck (1961) to the Dothan Formation of Late Jurassic age. Near Roseburg, Oregon, the part of the Myrtle Formation of Diller (1898) that was described as the Dillard Series by Louderback (1905) also seems likely to be correlative with the Franciscan (Irwin, 1960). Farther north in Washington, Canada, and Alaska are other similar rocks, some of which might be correlated with the Franciscan, as it forms only a small part of a great circum-Pacific belt of thick Mesozoic eugeosynclinal deposits. This belt also is characterized by the coincidence of serpentine intrusions (Hess, 1955), low-grade metamorphic rocks of the zeolite (Coombs, 1960), blueschist (Schurmann, 1951), and greenschist facies, and by modern oceanic troughs, volcanism, and seismic activity.

In summary, the Franciscan, as restricted to California, is distributed over an area of as much as 75,000 square miles, if one includes its total terrestrial and offshore extent, although the total area of outcrop is a little less than 15,000 square miles. The total area of deposition of Franciscan and other correlative eugeosynclinal rocks, however, extended not only through the length of California, a distance of 750 miles, but also for hundreds of miles beyond the State boundaries and over a width of a little more than 100 miles.

THICKNESS OF THE FRANCISCAN

The thickness of the Franciscan doubtless is great, but this cannot be ascertained by conventional stratigraphic methods because of the intensity of deformation, the lack of reasonably continuous exposures, and the absence of recognizable horizons or sequences that might be used to tie partial sections together. Reasonable estimates of a minimum thickness can be made by several methods, but even speculations on the maximum thickness are ruled out because the base is not known. Several features suggest the Franciscan must be very thick, but none of these leads to a close estimate of thickness. The occurrence of highly deformed

Franciscan rocks in belts, having a width of several tens of miles across the tectonic grain, but with no exposures of a basement and few inliers of younger rocks, leads to the assumption that the Franciscan is tens of thousands of feet thick. Similarily, the fact that in several places volcanic accumulations many thousands of feet thick are enclosed in still thicker sedimentary rocks suggests thicknesses in excess of 10,000 feet. In contrast, we find that the more reliable statements of thickness made by geologists, who studied a dozen different areas, range from 2,700 to 20,000 feet, with thicknesses in the 5,000- to 10,000-foot interval being the most common. These thicknesses apparently were thought to be partial sections measured on reasonably cohesive blocks of Franciscan rocks, rather than the total thickness to be found in each area. No one has been able to construct a composite total section by tying together partial sections by means of matching key horizons or sequences.

The problem of thickness is further complicated by the fact that the eugeosynclinal assemblage probably consists of more than one sequence of rocks that are similar lithologically but separate in time, with some of the younger part seemingly formed by cannibalism of the older. If some of the older sequence is locally eroded to provide the debris to form a younger sequence, how is this taken into account in a meaningful statement of the total thickness of the Franciscan? It is obvious that the thickness of the Franciscan where overlain by the Knoxville, of Late Jurassic age, bears no relation to the thickness where the Franciscan is of mid-Cretaceous age.

An approximation as to the minimum total thickness might be made by adding together minimum total thicknesses of sections thought to have been deposited at different times. McKee (1958a) reports a measurable thickness in the Pacheco Pass area of 4 miles, with an additional 2 miles of rocks believed also to be present. These rocks are probably pre-Knoxville in age, as they seem to be overlain by Knoxville sedimentary rocks, are in part regionally metamorphosed, and contain no K-feldspar (see pp. 139). To this Jurassic section of about 30,000 feet, we might add a section of mid-Cretaceous age exposed in the southern part of Marin County, which, according to J. Schlocker (oral communication, 1960), is about 9,000 feet thick. The age of this section is based on the presence of small amounts of K-feldspar in some of the graywacke and on sparse fossil data. In addition, rocks of very early Cretaceous age are known to be included in the Franciscan, but we know of no estimate of their thickness. If we assume that they are as thick as the mid-Cretaceous sequence, we arrive at an approximation of about 50,000 feet for the entire eugosynclinal assemblage. This estimate of thickness, while very large, seems reasonable when it is compared with the 40,000 or more feet of contemporaneous miogeosynclinal sedimentary rocks present in the bordering Great Valley.

A consideration of the significance of the metamorphic grade of regionally metamorphosed parts of the Franciscan gives an independent clue to its total thickness. As is discussed in further detail in the section on metamorphic rocks (see pp. 111), the blueschists, and especially the aragonite found in them, indicate that these parts of the Franciscan were subjected to a load equivalent to at least 50,000 feet of overlying rock. Further, for the metamorphic assemblages to have persisted, the rocks must have been uplifted and eroded quickly after their deposition, thereby indicating that the 50,000 feet is a measure of the thickness of the Franciscan rocks and not an indication of the quantity of rocks deposited on it in some younger period.

CLASTIC SEDIMENTARY ROCKS

Clastic sedimentary rocks form nearly 90 percent of the assemblage of Franciscan rocks and probably nearly 90 percent of these are dirty, unsorted sandstone or graywacke, with the remainder being mainly siltstone or shale. Conglomerate, although locally prominent, is quantitatively unimportant. The clastic sedimentary rocks, except for the conglomerate, are characterized physically, by being composed of angular and poorly sorted grains; mineralogically, by a high content of feldspar and rock fragments; and chemically, by an abnormally high ratio of soda to potash. Sandstones are dominantly feldspathic and lithic graywackes, which locally grade to tuffs, but some have so little matrix that they might be classed as arenites. Siltstones and shales are apparently quite similar to the graywackes though finer grained; they could be termed micrograywackes, since they contain an abnormally large amount of minute mineral grains and a small amount of clay minerals.

Graywacke

By far the most abundant rock of the Franciscan is graywacke, which has a truly astonishing volume. Even if the average thickness of the Franciscan is regarded as only 25,000 feet, and the depositional area in California and offshore is about 75,000 square miles, the total volume of the Franciscan graywacke is more than 350,000 cubic miles. To make this large figure more meaningful we might point out that this is sufficient sand to cover the State of California to a depth of 10,000 feet or the entire conterminous United States to a depth of 600 feet. As might be expected in a unit of this great bulk and areal extent, the Franciscan graywacke is not everywhere the same, nor has it been studied sufficiently to permit definition of the limits of its variation. Systematic changes, either spatially or temporally, have not been identified, except for K-feldspar content in some areas.

Much of the available data regarding the Franciscan graywacke deals only with a specific area studied as a basis for a thesis, and few geologists have attempted a

study of regional variation, provenance, or source. The conclusions of those who have considered the broader problems are repeated briefly here, prior to descriptions of the rock, so that the reader will have a better appreciation of the conflicting views that have been expressed and the difficulty of synthesizing the data.

Davis (1918b), summarizing what was then known of the "Franciscan sandstone," included admirable descriptions of some of the unusual sedimentary features shown by the rocks in the San Francisco Bay area, general statements of mineral content, and information on the more common heavy minerals. He concluded that most of the graywacke was a continental deposit laid down by streams in a region sufficiently arid that decay of rock minerals was very slight.

Taliaferro (1943a) presented considerably more factual data, including some heavy mineral and chemical analyses of graywackes, and he suggested that the graywackes show a southerly increase in quartz, sphene, epidote, tourmaline, and biotite, which increase he attributed to a difference in source rocks. Taliaferro (1943a, p. 139) believed that the Franciscan graywacke

"* * * was derived from a high, rugged, recently uplifted land mass under rigorous climatic conditions, high rainfall, and possibly a cold climate in the highlands with well-wooded lower slopes. The rivers from this area were large and of high gradient and brought down great floods of unaltered detritus into a shallow sinking basin. The land mass from which the greater part of the Franciscan detritus was derived was made up of granodiorite, crystalline schists, quartzites, recrystallized black cherts, and numerous intrusions of quartz and feldspar porphyries."

Soliman (1958) made a detailed study of the graywacke in the Isabel-Eylar area, east of Mount Hamilton, and compared these rocks with a few specimens from areas north of San Francisco and as far south as the San Benito quadrangle. As a result of the examination of several hundred thin sections, 135 of which were point counted to determine mineral percentages, and 30 heavy mineral analyses, he concluded that the graywackes in northern California have less maturity and contain a greater percentage of rock fragments and less quartz and feldspar than do graywackes in the Diablo Range. He found that epidote decreased from north to south and also from west to east. Soliman concluded that the Franciscan sediments were deposited in a great trough that was filled chiefly from the north, with some additions from the sides. Variations in graywacke were attributed primarily to a north-to-south change in relief of a landmass lying east of the trough, and secondarily to the distance from the major source to the north. An unusual abundance of pink sphene, hypersthene, diopsidic augite, pink garnet, and hyacinth zircon in the Diablo Range was attributed to local derivation of those minerals from a landmass of pre-Mesozoic metamorphic and igneous rocks lying to the west.

Bailey and Irwin (1959) studied the regional variation in K-feldspar content of graywacke in both the northern Coast Ranges and the western border of the Great Valley. In successively younger Mesozoic rocks of the Great Valley, they found a systematic increase in the quantity of K-feldspar, with the average ranging from half a percent in rocks of Late Jurassic age to more than 10 percent in rocks of Late Cretaceous age. Graywackes in the northern Coast Ranges were divided into two units on the basis of their K-feldspar content. One unit, lying generally in the western half of the Coast Ranges and at least in part of mid-Cretaceous age, was found to have an average K-feldspar content of about 8 percent; it was referred to as the "rocks of the coastal belt" and excluded from the Franciscan Formation. The other unit, comprising a central belt in which most of the samples contained little or no K-feldspar, was assigned to the Franciscan; and graywackes in the same area with anomalously high content of K-feldspar were thought to be explained by infolding or infaulting of younger rocks.

Occurrence and megascopic features. Exposures of Franciscan graywacke are in most places poor and discontinuous. Areas of Franciscan sedimentary rocks usually are mantled by at least a few feet of light-colored soil, through which protrude small knobs of the underlying rock. The best and most continuous outcrops occur in the main stream canyons, but even here rocks generally crop out only over the width of the stream at flood stage. In some areas, however, especially where more recent uplift is particularly pronounced, as in parts of the northern Coast Range and in diapiric plugs like those of Mount Diablo and New Idria, massive graywacke forms well-exposed cliffs a few hundred feet high. Excellent artificial exposures have been provided in recent years by cuts being made by highways, roads, quarries, or large buildings. In most areas, however, the fragmentary nature of the exposures permits observation of only small-scale details of sedimentary structures or bedding and does not allow tracing of a specific bed for more than a short distance. Thus, little is known about the continuity or lenticularity of individual beds.

Bedding of the Franciscan graywacke is best characterized by both the irregularity in thickness of the beds and the unusually great thickness of some of them. Single units, as defined by the distances between shale partings or interbeds, have thicknesses ranging from half an inch up to at least tens, and perhaps hundreds, of feet. Although there is an apparent tendency for beds in some areas to be unusually thick or unusually thin, no rhythmic pattern to the variation in thickness has been detected. Commonly a well-exposed section will show a variation in bed thicknesses from an inch up to perhaps as must as 10 feet, with all intermediate thicknesses represented and distributed through the section at random. The quantity of shale present as parting layers between graywacke beds is generally small, amounting to less than a fifth of the

Photo 7. Massive Franciscan graywacke; no bedding apparent in lower 40 feet of exposure. Big Austin Creek, Skaggs quadrangle.

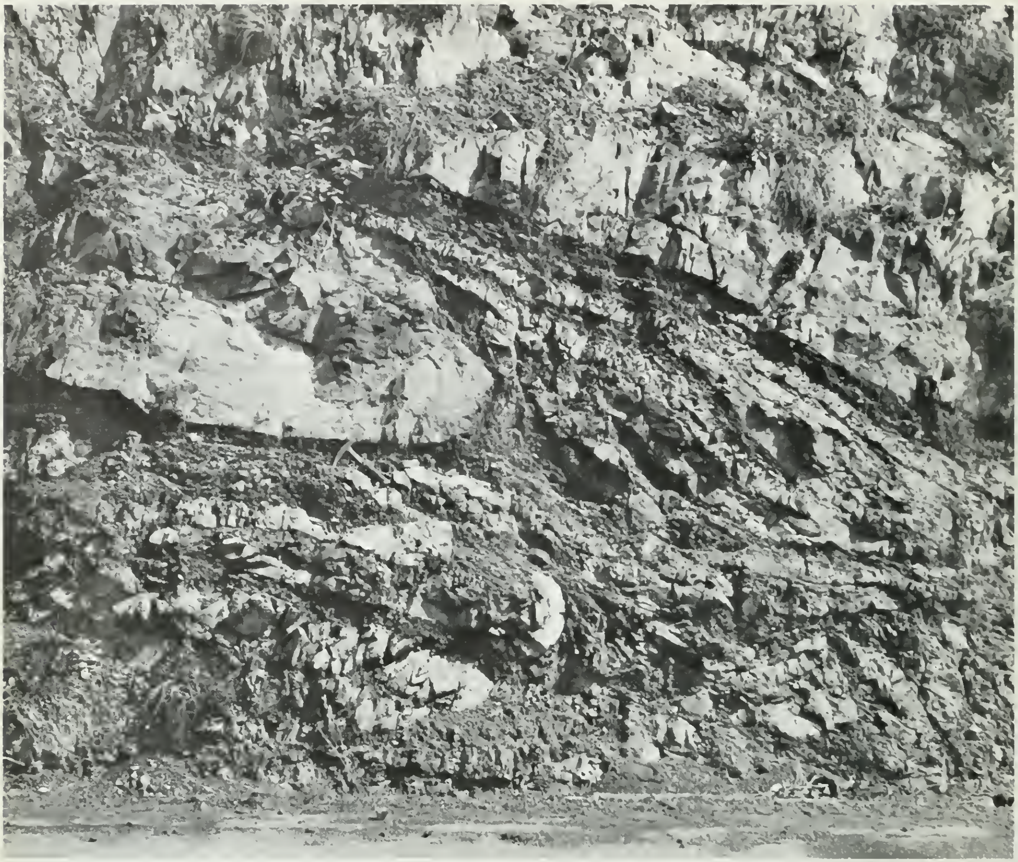


Photo 8. Tightly folded Franciscan (Coastal belt) graywacke and shale. On Highway between Fart Bragg and Willits, east side af Glenblair quadrange. Note hammer left af center for scale.

graywacke-shale sequence, but no relation between the quantity of shale and the thickness of the graywacke beds has been noted.

Sedimentary structures of the Franciscan graywacke have not been studied in detail, but our observations indicate that most of the graywacke beds are non-graded and possess little internal structure other than a vague platy lamination which is due to alignment of flat shale chips and bits of carbonaceous matter. Sole markings, ripple marks, crossbedding, and graded bedding have been seen only in a few areas. Locally in the Franciscan outcrop belt, the usual thick graywacke beds are replaced by thin graywacke beds alternating with siltstone or by a sequence in which shale and siltstone predominate. In some of these finer grained sequences sedimentary structures are unusually abundant.

The area about Mount Hamilton, in the Diablo Range, is one in which rhythmically alternating beds of graywacke and siltstone or shale form a large part of the total sedimentary sequence. In this area the graywacke generally shows well-developed graded bedding, with beds ranging in thickness from less than an inch to several feet. The upper shaly portion of many of these graded beds is finely laminated and may exhibit small-scale crossbedding. Large-scale crossbedding has not been observed in the graywacke here or elsewhere, and convolute bedding is uncommon. The contact between successive graded units generally is sharp. Sole markings, including both groove casts and flute casts, have been observed at the base of some beds, but these markings rarely can be seen owing both to the lack of adequate exposures of the undersides of beds, and, at least to some extent, to oblitera-

tion of sole markings by shearing along bedding planes. In this area carbonaceous material is abundant, particularly in the upper parts of graded beds and in the overlying fine-grained siltstone and shale. Most of this material consists of degraded, shredded bits of charcoal which in places retains cellular structure.

In many places where graywacke beds are thin, they can be seen to be lenticular, but much of this lenticularity is a secondary feature resulting from development of shear planes that intersect bedding planes at low angles. Where shear planes are closely spaced, their intersection with bedding planes forms well-developed boudinage, but more commonly the combination of irregular thickness of beds and irregular spacing of shear planes results in a chaotic jumble of short bed segments and lenticles. Not uncommonly during deformation, shale has been injected plastically into fractures in the graywacke, thus forming planar surfaces between massive graywacke and shale that can be easily mistaken for normal bedding planes. However, the bedding of otherwise massive graywacke can, in some places, be determined by the orientation of mica, shale flakes, or bits of carbonaceous material. This method provides a means of checking whether a thin shale parting is a bed or is material that has been plastically injected along a fracture.

The appearance of fresh Franciscan graywacke varies with differences in grain size, proportions of the component minerals and rock grains, and the amount of pressure it has undergone. All varieties, however, are well indurated, poorly sorted, dirty sandstones containing abundant quartz, feldspar, and some rock fragments. The predominant color of fresh specimens is gray, but may range from light to dark gray to

Photo 9 (below). Thick-bedded Franciscan graywacke, with minor beds of black shale. Road cut in sea cliff about five miles southeast of Crescent City, Del Norte County. Note hammer below center for scale. *(Photo by Salem Rice.)*

Photo 10. Tightly folded and faulted Franciscan(?) shale and thin-bedded graywacke in quarry one mile south of Novato. Several specimens of *Inoceramus schmidti* of Campanian age have been found in these beds.

bluish or greenish gray. Upon weathering, the color changes first to lighter gray and then to tan. Hydrothermal alteration may change the color to nearly white.

Most of the graywacke appears on cursory inspection to have an average grain size of about half a millimeter, but this appearance is somewhat misleading as the rock is poorly sorted and one tends to overestimate the average grain size when disregarding the finer grains. The grains range in shape from dominantly angular to subangular and, more rarely, subrounded. Typical specimens, especially if not entirely fresh, have a "salt and pepper" aspect, owing to the prominence of white feldspars and black grains of shale, mafic rocks, or carbonaceous material. In addition, many contain larger flakes of shale and shiny flakes of mica, either muscovite or biotite. Much of the graywacke appears merely very well compacted, but in some areas it has been so compressed that the shale and mafic rock fragments have been flattened and impart a slight schistosity to the rock, forming what is sometimes referred to as a semischist. The graywacke is dense and virtually nonporous. In many specimens it is difficult to distinguish with a hand lens any material that would be called matrix. Although the graywacke is generally well indurated and hard, many beds are cut by innumerable invisible cracks and are so shattered that it is difficult to collect a piece the size of a hand specimen. Veining by quartz or calcite is widespread, and locally veins of adularia, albite, or laumontite are found.

Microscopic features. Thin-section study reveals wide diversity among rocks that are now grouped together as Franciscan graywacke, but quantitative data on the components generally are difficult to ob-

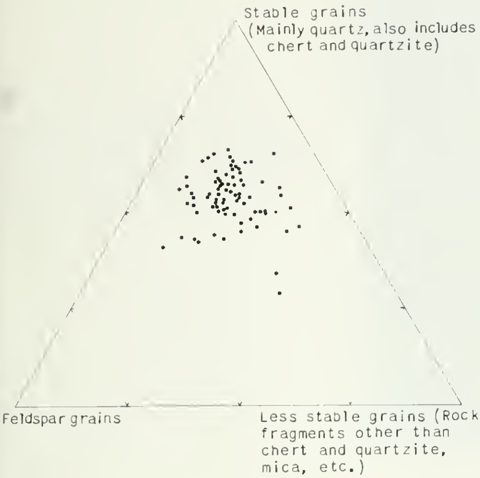


Figure 4. Ternary diagram showing proportions of stable grains, less stable grains, and feldspar grains in 80 Franciscan graywackes (54 northern California, 26 central California). Matrix not included. From Soliman (1958).

tain. This difficulty is chiefly because many of the feldspars are fresh and untwinned, and thus they are not easily distinguished from quartz, and much of the plagioclase is albite that is scarcely distinguishable from K-feldspar. The finest grained material of the matrix is generally unresolvable, and measurement of even the quantity of matrix is difficult, because in many of the rocks there is a gradation rather than a sharp break in size between clasts and matrix. Some of the difficulties of measurement might be overcome by the application of preferential stains to the plagioclase and K-feldspar (Bailey and Stevens, 1960), but because these methods have not yet been applied to thin sections of these rocks, the available data on quartz/feldspar or plagioclase/K-feldspar ratios obtained from thin sections cannot be considered as entirely reliable. Grain counts made following a separation of light and heavy fractions are probably little better because of the same inherent difficulties, and, in addition, the graywacke is so indurated that treatment drastic enough to separate individual grains also will shatter or dissolve some of the components. Thin sections, however, do reveal features not discernable with a hand lens, and the estimates that have been made of component percentages give a general idea of the variability found among the graywackes even though these estimates do not permit one to place rigid limits on the variations or to be confident of any regional variation.

The predominant features seen in thin section are the general lack of abrasion and the lack of sorting of the grains of the rock. Most of the grains are angular, and this is especially true for the monomineralic grains. Rock fragments tend to be subangular or subrounded, but in many sections the compaction of the rock has led to a modification of the shape of the softer composite rock fragments by their yielding to fit between the monomineralic grains. The monomineralic grains are chiefly feldspar and quartz, but most sections contain a few grains of epidote-group minerals, apatite, and zircon. The quantity of rock fragments ranges from near zero to as much as three-fourths of the rock. In many sections the predominant rock fragments are mafic lava, apparently quite like the greenstone in the assemblage of Franciscan rocks, and all gradations between such volcanic-rich graywackes and tuffs are known. Other lithic graywackes contain very few mafic rock fragments but instead contain clasts of shale, chert, quartzite, or quartz-sericite schist.

Most of the Franciscan graywacke has a matrix content of at least 10 percent and thus would fall into the "wacke" classification of Gilbert (Williams and others, 1954, p. 292). Of 80 specimens point counted by Soliman (1958), about 42 percent would fall into the arkosic wacke subdivision, 23 percent into the feldspathic wacke subdivision, and 35 percent into the lithic wacke subdivision (fig. 4).

Quartz grains make up from 10 to 50 percent of most of the Franciscan graywackes, with the average of available measurements being about 30 percent. The average value of normative quartz in the 21 chemical analyses of Franciscan graywacke included with this report is 31.5 percent. Extreme values for quartz grains of 5 to 60 percent based on point counts of thin sections are recorded by Soliman (1958), and his range for "stable grains," shown in figure 4 is from 23 to 62 percent. Soliman's values for quartz and "stable grains" are high as compared with measurements made by others, and with chemical analyses. The quartz grains are generally angular to subangular, but rare rounded or even euhedral grains are present. Most quartz grains are clear, and many contain minute liquid- and gas-filled cavities. Many show undulatory extinction, and some grains are composite, consisting of several crystal units separated by sutured boundaries.

Feldspar generally is the dominant mineral in the graywackes and, in some specimens, probably amounts to as much as 60 percent of the rock. Feldspar occurs most abundantly as monomineralic grains, but it is also a prominent constituent of many of the rock fragments. The percent of clastic feldspar grains in 80 graywacke specimens from northern and central California was determined by point counts by Soliman (1958). Figure 4, taken from his report, indicates feldspar amounts to from 9 to 46 percent of the clastic grains, with more than half the specimens containing

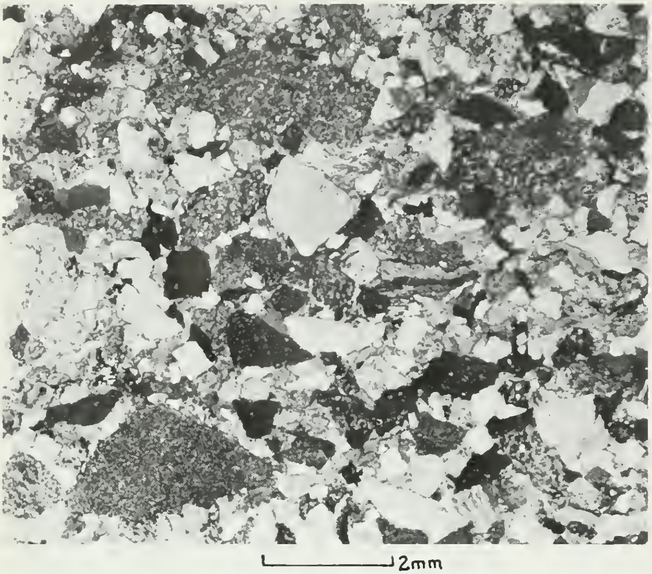


Photo 11 (left). Lithic graywacke with clasts of greenstone, altered mafic glass, shale, chert, quartz, orthoclase, plagioclase, epidote, biotite, and myrmekite: Tombs Creek quadrangle. (Coastal belt unit) (58-274).

Photo 12 (right). Feldspathic graywacke with clasts of quartz, albite, muscovite, biotite, chlorite, mafic volcanic rocks and glass, and shale. Pillsbury Lake quadrangle (B-35).

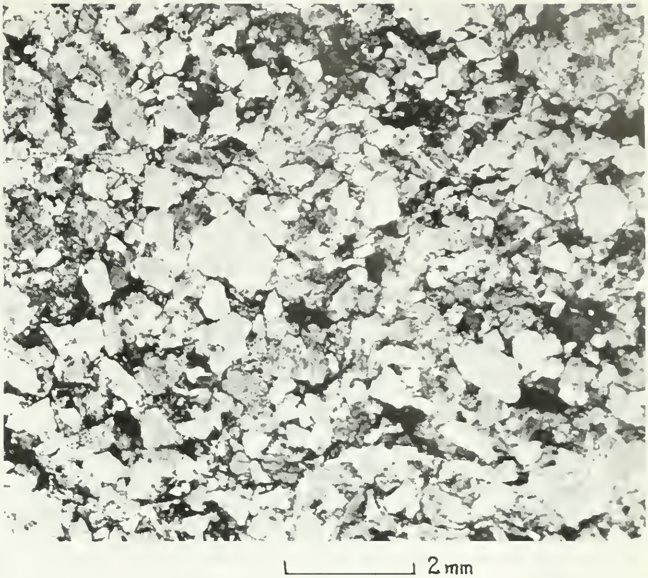


Photo 13 (right). Feldspathic graywacke with quartz, plagioclase, orthoclase, muscovite, biotite, epidote, mafic volcanic rocks, and shale. Fort Ross quadrangle. (Coastal belt unit) (60-305).

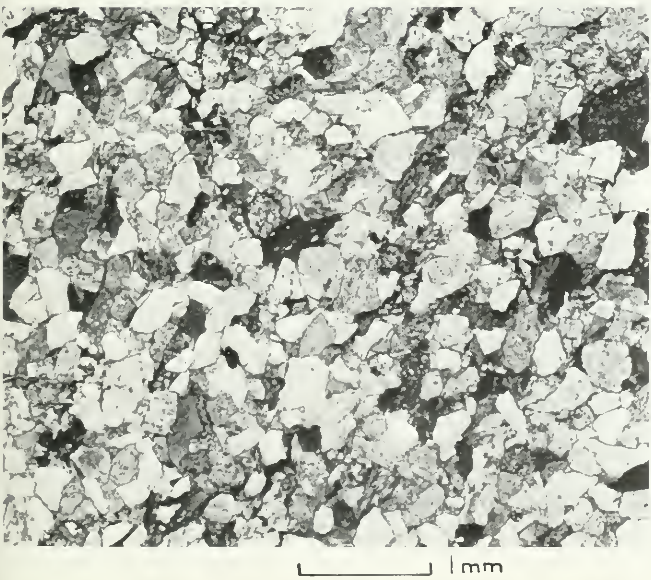


Photo 14 (left). Feldspathic graywacke with quartz, plagioclase, orthoclase, biotite, epidote, mafic volcanic rocks, and shale. Very little matrix. Fort Ross quadrangle (58-191).

between 20 and 30 percent. The average value of normative feldspar in 21 analyses of Franciscan graywackes is 43.5 percent. Grain counts or point counts reported by Soliman and others are probably all low with respect to total feldspar, because the grain counts are made on a light fraction that does not include the mafic feldspar-bearing rock fragments and point counts normally include only the monomineralic grains. The minimum and maximum for feldspar content is the 5 to 55 percent reported for the Pacheco Pass area by McKee (1958a), and the average of all of the measurements and estimates we found in the literature is about 35 percent. Normative feldspar calculated from the available chemical analyses averages about 45 percent.

Over wide areas plagioclase is the only feldspar present as grains in the Franciscan graywacke; in some areas, however, orthoclase is also present. The plagioclase is highly sodic, and most investigators have reported it as either albite or oligoclase. Our thin-section studies indicate albite is most common, oligoclase less so, and andesine comparatively minor. Soliman (1958) reports that labradorite and bytownite also occur in minor amounts. Normative plagioclase calculated from analyses ranges from An_{01} to An_{32} and averages An_{15}. As the abundance of K-feldspar can apparently be used to separate otherwise indistinguishable sequences of graywacke, and also has genetic implications as to possible source areas, it is discussed elsewhere in the report in considerable detail (see pp. 139 et seq.).

The feldspar grains, though tending to be more nearly square or rectangular, are comparable in size and angularity to the quartz grains. Many show no twinning, but in some sections they can be distinguished from quartz because they are more cloudy and more susceptible to incipient alteration. Some are composite and appear to have been replaced by groups of smaller crystals of a different kind of plagioclase.

The quartz/feldspar ratio has been measured by various means or estimated by at least two dozen geologists, who report figures ranging from 1:2 to 10:1. The point counts of Soliman (1958) indicate a ratio of siliceous grains, including chert, to feldspar of 2:1 (see fig. 4), but his values for the siliceous grains seem to be high. The average of all of the data available is very close to 1:1. Norms calculated from chemical analyses of 21 graywackes indicate an average ratio of 3 quartz to 4 feldspar, but it should be recognized that some of the normative quartz is present as chert or quartzite, and some of the normative feldspar represents material occurring in rock fragments. We have no data indicating a difference in quartz/feldspar ratios between the graywackes with K-feldspar and those without, but a significant difference may exist.

Rock fragments are the next most abundant component of the graywackes, but they have received little study. Reported percentages of rock clasts range from a minimum of 2 to a maximum of 55, but as the volcanic graywackes apparently grade into tuffs with an increase in volcanic fragments and an elimination of nearly all of the quartz, the reported maximum of 55 percent is rather arbitrary. Even less information is available on the proportions of the various kinds of rock fragments, and nothing has been noted regarding the relation of the total quantity to kind of rock fragment.

The most abundant rock clasts are various kinds of fine-grained mafic volcanic rocks, apparently like the greenstone flows, tuffs, and breccias that are interlayered with the sedimentary rocks. Altered mafic glass fragments are very common, and minute fragments of altered glassy material seem to provide the major part of the matrix for many of the more lithic graywackes. Chert fragments also are common, and some of these that are red and contain radiolaria resemble those found in rhythmically layered sequences of the Franciscan Formation. Other chert fragments, which are common in some of the graywackes, are black and carbonaceous; they seem to be unlike any found as beds in the Franciscan. Recrystallized cherts, many of which contain shreds of mica, are also common. Shale fragments are a ubiquitous component, but pieces of fine-grained graywacke are rare. McKee (1958a) reports that in the Pacheco Pass area detrital grains of quartz diorite are prominent in the part of the Franciscan that he believes to be the oldest exposed. Fragments of quartz-mica schists are not uncommon, but clastic grains of glaucophane schist or

Figure 5. Ternary diagram showing proportions of stable grains, unstable grains, and matrix in 79 Franciscan graywackes (51 northern California, 28 central California). From Soliman (1958).

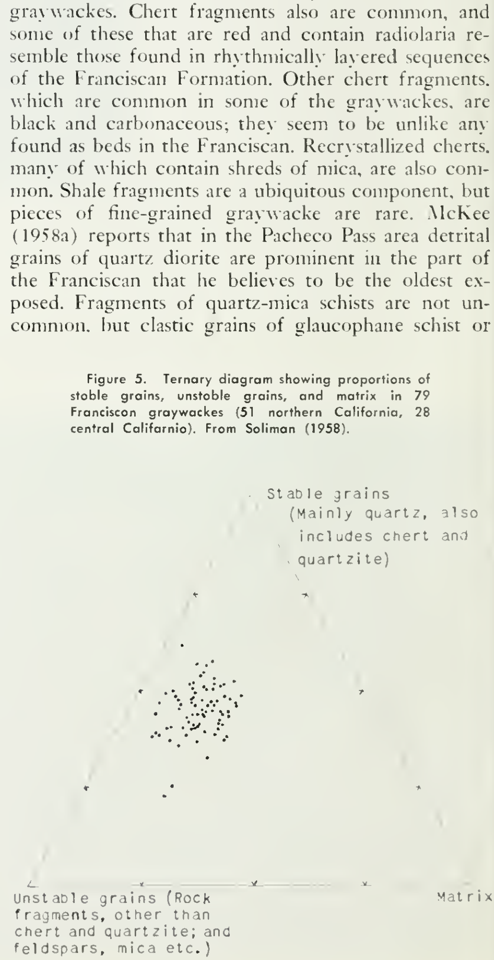


Figure 6. Heavy minerals in Franciscan graywackes.

Quadrangle	Actinolite	Allanite	Andalusite	Apatite	Augite	Biotite	Brookite	Calcite	Cassiterite	Chlorite	Chromite	Clinozoisite	Epidote	Garnet	Gahnite	Glaucophane	Hematite	Hornblende	Hypersthene	Idocrase	Kyanite	Ilmenite	Lawsonite	Leucoxene	Magnetite	Monazite	Muscovite	Oxyhornblende	Piedmontite	Picotite	Pumpellyite	Pyrite	Rutile	Sphene	Tourmaline	Tremolite	Zircon	Zoisite
1. Blue Lake		X					X																															
2. Ferndale-Fortuna				X			X					X																						X	X		X	X
3. Blocksburg	X												X	X			X	X	X		X				X			X						X	X		X	
4. Leggett			X															X						X		X							X				X	X
5. Covello														X																			X	X			X	
6. Anthony Peak						X		X																										X			X	
7. Branscomb				X								X						X					X			X								X				
8. Willits				X		X						X						X																X				
9. Lower Lake																																						
10. Sebastopol				D	X	X				X		X	X	X				X							X		X					X	X	X	X			
11. Sebastopol																																	X					
12. San Francisco North			X	X	X		X		X			X	X	X	X			X	X		X	X		X		X	X			X	X	X		X	X	X	X	X
13. San Francisco South				X									X	X					X			X			X									X	X	X	X	
14. San Jose-Mount Hamilton				X								X	X					X			X									X					X		X	X
15. Isabel-Eylar	X				X	X					X			X	X	X		X	X			X	X	X	X				X						X	X	X	
16. Mount Boardman																																						
17. Quien Sabe																																						
18. Ortigalita Peak																																						
19. San Simeon				D		X				X				X				X							X							X			X			
20. Adelaida				D						X		X						X							X							X			X			
21. Adelaida				D		X				X				X				X				X										X			X		X	X
22. Santa Maria					X					X								X	X	X				X	X								X					

1. Manning, G. A., and Ogle, B. A. (1950, p. 19)
2. Ogle, B. A. (1953, p. 14)
3-8,22. Stanford University students under G. A. Thompson, 1956
9. Brice, J. C. (1953, p. 13) Thin-section studies only.
10. Johnson, F. A. (1934)
11. Travis, R. B. (1952, p. 13) Thin-section studies only.
12-13. Schlocker, Julius (oral communication, 1960)
14. Crittenden, M. D., Jr. (1951, p. 18)
15. Soliman, S. M. (1958)
16. Maddock, M.E. (1955)
17. Leith, C. J. (1949, p. 14) Thin-section studies only.
18. Briggs, L. I. (1953a, p. 14) Thin-section studies only.
19-20. Dosch, E. F. (1932)
21. Goudy, C. L. (1936)

= >5 percent of heavies, or "common"
X = <5 percent of heavies, or "rare"
D = Destroyed by treatment, if present

jadeitized rocks have been reported only by McKee (1958a). The shapes of the rock fragments are variable. In many graywackes, the fragments of relatively weak rocks, such as the mafic volcanics, have been bent to fit between the harder grains, while the harder rocks, such as the cherts, are undeformed.

Estimates of the quantity of matrix in these graywackes range from 8 percent to as much as 50 percent, but probably these have been made on different bases by different geologists. In many of the graywackes there is no clearly discernible break in grain size between the coarsest clasts and the finest matrix material, and, as a result, the distinction between clasts and matrix is arbitrary. The problem is further compounded if slight metamorphism has resulted in the growth of new crystalline aggregates, some of which are larger than the smallest of the original clasts. In general, however, geologists include under the term "matrix" the dark-colored and nearly unidentifiable paste, which probably has a grain size of less than 0.02 mm. In spite of the difficulty of measuring the quantity of matrix, it is obvious that the quantity varies considerably; in some graywackes the clasts appear largely separated by matrix, while in the majority the grains appear closely packed with only narrow films of matrix between them. Figure 5 shows that the quantity of matrix, as determined by Soliman (1958) by point counts on 80 Franciscan graywackes, is generally between 5 and 25 percent.

The nature of the matrix material is largely indeterminate in thin section, but much of it appears to be sericitic or chloritic. An X-ray study of the finest fraction obtained from crushed graywacke of the San Francisco Bay area by J. Schlocker (oral communication, 1963) indicates mica is more abundant than chlorite, except in some volcanic-rich wackes, and there is little, if any, kaolinite. Both the mica and chlorite are fairly well ordered but some contain a low percentage of expandable layers. Calculations of norms also indicate chlorite is generally more abundant than kaolinite and may exceed muscovite, but this would include components in rock grains as well as in the matrix. In some graywacke the original matrix is sufficiently recrystallized to permit one to identify new quartz, sericite, chlorite, and albite; however, most Franciscan graywackes are recrystallized so little that the margins of the clastic grains have not been rendered fuzzy by the growth of new minerals.

The cement for these hard tough rocks is generally just the paste or matrix. Recrystallized quartz is sometimes visible in the matrix of the more feldspathic graywackes, suggesting that their matrix is more siliceous than the average, and a higher proportion of chlorite is present in the matrix of graywackes with abundant mafic rock fragments. Occasionally one finds specimens with a true calcite cement, but, more commonly, calcite cement occurs in small irregular patches that suggest a selective replacement of the more normal matrix. Quartz also locally replaces most or all of the matrix, especially in areas in which all the graywackes show incipient metamorphism.

Other constituents of the graywackes are heavy detrital grains which are readily separated by the use of heavy liquids. More than 50 separations have been reported, and these are summarized in figure 6. In this table an attempt has been made to indicate abundance, even though not all of the data are comparable because of difference in both the treatment and reporting of results. The minerals most investigators find to be abundant are biotite, chlorite, minerals of the epidote group, sphene, and zircon; other apparently widespread minerals present in smaller amounts are apatite, garnet, hornblende, ilmenite, leucoxene, magnetite, pyrite, and tourmaline. More uncommon minerals include brookite, gahnite, kyanite, lawsonite, piedmontite, pumpellyite, and rutile. Chromite or picotite, which would be indicative of derivation from ultramafic rocks, are rarely reported even though several geologists have reported serpentine as one of the common lithic fragments in the graywacke. Much of the reported serpentine may be chloritized mafic glass, with which it is easily confused. Glaucophane, which is so readily recognized that it could scarcely be overlooked, was found as clastic grains in heavy concentrates only by Soliman (1958). Staurolite, which occurs in upper Mesozoic sedimentary rocks of the Great Valley (Briggs, 1953b), has not been found. Among the common heavy minerals are several (such as apatite, biotite, chlorite, and hornblende) that are relatively unstable and readily destroyed by weathering and abrasion. Andalusite, kyanite, piedmontite, and probably also lawsonite and pumpellyite, though not abundant, indicate that at least part of the source rocks were regionally metamorphosed.

Chemical features. The chemical composition of 21 representative graywackes is given in table 1, and the distribution of the sample localities is shown in figure 7. A comparison of the average of these analyses with graywackes found in other parts of the world can be made by reference to table 2. Prominent characteristics of Franciscan graywackes are: (1) soda commonly exceeds potash, or, expressed differently, the K_2O/Na_2O ratio is less than 1, (2) the ratio of ferric to ferrous oxide (Fe_2O_3/FeO) is generally less than 1, and (3) combined water (H_2O+) is generally more than 2 percent.

Molecular norms are also given in tables 1 and 2, and because not all geologists are familiar with this type of presentation of data, or the ease with which the molecular norms can be obtained from a chemical analysis, the method will be briefly explained. In the conversion of analyses given in weight percent of the constituent oxides into minerals, use is made of the molecular units of Niggli (1936), and the method of calculation follows that of Eskola (1954) and Barth (1955). The method is based on determining the number of cations of the various cationic elements in a unit volume of rock. This is done by first reducing the

Table 1. Analyses and molecular norms of Franciscan graywackes.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
SiO_2	56.8	67.3	68.5	68.8	71.7	71.2	72.2	62.7	67.5	67.2	58.4	70.7	72.9	70.3	69.0	68.9	67.0	67.3	60.9	67.1	70.8
TiO_2	n.d.	1.8	0.6	0.3	0.3	0.4	0.5	0.5	0.6	0.5	0.5	0.4	0.6	0.4	0.7	0.6	0.6	0.6	0.6	0.5	0.4
Al_2O_3	11.4	12.4	12.8	14.5	13.2	13.1	11.7	13.1	14.6	14.6	14.2	14.2	11.3	14.0	11.7	12.7	14.1	15.5	16.4	14.9	14.0
Fe_2O_3	1.5	0.6	1.3	0.6	0.3	1.0	0.7	2.1	2.7	1.9	2.4	1.8	1.1	0.8	1.0	1.5	0.9	0.4	1.4	1.0	0.6
FeO	5.0	4.0	3.4	2.5	3.6	2.4	3.2	1.3	1.9	2.3	1.4	1.3	2.8	2.6	4.2	2.8	4.0	3.8	4.4	2.9	2.5
MnO	0.2	0.1	--	--	--	0.1	0.1	0.1	0.1	0.1	0.2	--	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
MgO	3.1	2.3	2.2	1.9	1.8	2.2	2.7	1.3	1.7	2.3	1.2	1.3	2.7	2.1	3.8	2.5	2.8	1.9	3.1	1.6	1.7
CaO	7.6	3.3	1.8	2.2	1.8	1.5	0.6	6.0	1.1	1.8	8.2	0.7	0.6	1.3	1.3	1.9	1.3	0.6	3.9	2.0	1.5
Na_2O	3.3	3.0	6.0	3.9	2.7	4.3	3.2	3.6	3.7	3.7	3.3	4.3	3.8	4.1	2.0	2.7	3.4	4.2	4.2	3.1	3.7
K_2O	0.9	1.2	1.3	2.7	1.3	1.1	1.4	1.7	1.9	1.9	2.0	2.4	0.9	1.2	2.3	2.1	1.6	3.2	0.6	2.3	2.2
H_2O+	3.2	2.5	2.1	1.6	2.5	1.9	2.7	3.2	3.5	3.4	3.1	2.4	2.2	2.4	3.3	2.8	2.8	1.8	3.7	2.6	2.2
H_2O-	1.4	0.3	0.3	0.3	0.1	0.3							0.4	0.2	0.3	0.7	0.6	0.2	0.5	0.8	0.2
CO_2	5.1	0.6	n.d.	0.1	0.3	0.1	0.1	3.6	--	--	4.8	--	0.1	0.1	--	0.3	0.1	--	0.1	0.2	0.1
P_2O_5	0.1	0.1	0.2	0.4	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Total	[a]99.57	[a]99.41	[a]100.47	[a,b]100.13	[a,c]99.93	[a]99.85	99	99	99	100	100	100	99.72	[a]99.69	100	100	99	100	100	99	100
MOLECULAR NORM-CATANORM																					
Q	23.5	34.8	20.4	26.4	41.9	33.5	40.8	29.8	33.5	29.8	25.0	31.9	40.3	34.1	37.4	36.8	31.4	22.8	18.8	31.9	32.8
or	5.5	7.0	8.0	16.5	8.0	6.5	9.0	10.5	12.0	11.5	12.0	14.5	5.5	7.0	14.5	13.0	10.0	19.5	4.0	14.5	13.5
ab	31.0	28.0	54.5	36.0	25.5	39.5	30.0	33.5	35.0	35.0	30.5	40.5	35.5	38.0	19.0	25.5	32.5	38.5	39.0	29.5	34.0
an	4.5	12.5	4.3	8.0	6.5	5.5	1.0	6.0	5.0	8.5	9.0	2.5	0.5	5.0	5.5	7.0	5.0	2.0	18.0	8.0	6.5
C	4.0	2.2	--	2.5	5.9	3.3	5.3	3.7	5.2	4.0	3.9	4.1	4.5	4.9	4.7	4.2	5.7	4.9	2.9	5.2	3.7
en	9.0	6.8	6.2	5.4	5.2	6.6	7.8	3.8	5.0	6.4	3.4	3.6	7.8	6.0	11.2	7.2	8.0	5.4	9.0	4.8	4.8
fs	7.0	3.4	3.2	3.0	5.0	2.4	3.8	--	--	1.8	--	--	3.0	3.0	0.5	2.6	5.0	5.4	5.0	3.2	2.8
mt	1.6	0.8	1.4	0.8	0.3	1.2	0.8	2.1	3.0	2.1	2.5	2.0	1.2	0.9	1.2	1.6	0.9	0.4	1.5	1.2	0.8
il	--	2.6	1.0	0.4	0.6	0.6	0.8	0.6	1.0	0.6	0.6	0.6	0.8	0.6	1.0	1.0	1.0	0.8	1.0	0.8	0.6
hm	--	--	--	--	--	--	--	0.1	--	--	--	--	--	--	--	--	--	--	--	--	--
ap	0.3	0.3	0.5	0.8	0.3	0.3	0.3	0.3	0.3	0.3	0.5	0.3	0.3	0.3	0.5	0.3	0.3	0.3	0.6	0.3	0.3
cc	13.6	1.6	0.5	0.2	0.8	0.6	0.4	9.6	--	--	12.6	--	0.6	0.2	--	0.8	0.2	--	0.2	0.6	0.2
MOLECULAR NORMS MAKING USE OF COMBINED WATER																					
Q	21.0	35.9	21.9	25.9	40.9	34.3	41.1	30.0	34.0	30.5	24.6	31.0	39.8	33.5	39.0	37.5	31.8	24.6	19.9	32.7	32.3
or	--	3.0	8.0	14.5	--	--	--	2.5	--	3.0	4.5	8.0	--	--	5.5	5.0	--	9.0	--	3.0	8.5
plag	35.5	40.5	58.8	44.0	32.0	45.0	31.0	39.5	40.0	43.5	39.5	43.0	36.0	43.0	24.5	32.5	37.5	40.5	57.0	37.5	40.5
chl	13.4	8.5	7.9	7.2	8.5	7.5	9.6	3.1	4.1	6.9	2.9	3.0	9.0	7.5	13.5	8.1	10.9	9.0	11.6	6.6	6.4
kaol	3.6	1.2	--	3.4	5.4	1.4	3.4	1.0	0.8	1.2	1.8	3.6	4.6	4.2	2.2	2.0	3.4	--	2.6	1.2	3.4
ms	7.7	5.6	--	2.8	11.2	9.1	12.6	11.2	16.8	11.9	10.5	8.5	7.7	9.8	12.6	11.2	14.0	14.7	5.6	16.1	7.0
mt	1.6	0.8	1.4	0.8	0.3	1.2	0.8	2.1	3.0	2.1	2.5	2.0	1.2	0.9	1.2	1.6	0.9	0.4	1.5	1.2	0.8
il	--	2.6	1.0	0.4	0.6	0.6	0.8	0.6	1.0	0.6	0.6	0.6	0.8	0.6	1.0	1.0	1.0	0.8	1.0	0.8	0.6
hm	--	--	--	--	--	--	--	0.1	--	--	--	--	--	--	--	--	--	--	--	--	--
ap	0.3	0.3	0.5	0.8	0.3	0.3	0.3	0.3	0.3	0.3	0.5	0.3	0.3	0.3	0.5	0.3	0.3	0.3	0.6	0.3	0.3
cc	13.6	1.6	0.5	0.2	0.8	0.6	0.4	9.6	--	--	12.6	--	0.6	0.2	--	0.8	0.2	--	0.2	0.6	0.2
																		C=0.7			
%An in plag	13	31	7	18	20	12	3	15	12	20	23	6	1	12	22	22	13	5	32	21	16

1. "Neocomian Sandstone" from headwaters of Bagley Creek, Mount Diablo, Calif. (Turner, 1891, p. 412). Analysis by W. H. Melville.
2. Graywacke (NA 450), New Almaden district, Santa Clara County, Calif. Analysis by Mrs. A. C. Vlisidis.
3. Franciscan "sandstone," Sulphur Bank, Calif. (Becker, 1888, p. 82). Analysis by W. H. Melville.
4. Franciscan "sandstone" from quarry of Oakland Paving Co., Piedmont, Alameda County, Calif. (Davis, 1918b, p. 22). Analysis by J. W. Hanson.
5. Franciscan "sandstone," junction of Buckeye Gulch and Hospital Canyon, Carbona quadrangle, Stanislaus County, Calif. (Taliaferro, 1943a, p. 136). Analysis by Herdsman Laboratory, Glasgow.
6. Graywacke (302/74), Valley Ford, Sebastopol quadrangle, Sonoma County, Calif. (Bloxam, 1956, p. 493). Anaysis by E. H. Oslund.

7-12. By rapid rock analysis method described in U. S. Geol. Survey Bull. 1036-C Analyses by P. L. D. Elmore, I. H. Barlow, S. D. Botts, and Gillison Chloe. H_2O treated as combined water in calculating molecular norms.

7. Franciscan graywacke (59-76) from saddle 4,900 ft N. 54° W. of Bummer Peak, Skaggs Springs 7½-minute quadrangle, NE¼ of Skaggs quadrangle, Sonoma County, Calif.
8. Franciscan graywacke (59-108) from 450 ft N. 40° W. of "peak 1135" near center of east edge of Skaggs Springs quadrangle, Sonoma County, Calif.
9. Franciscan graywacke (59-358) from 3,150 ft S. 85° W. of Gabes Rock, Cazadero 7½-minute quadrangle, SE¼ of Skaggs quadrangle, Sonoma County, Calif.
10. Franciscan (coastal belt) graywacke (59-337) from saddle 1,200 ft south of The Nubble, Tombs Creek 7½-minute quadrangle, NW¼ of Skaggs quadrangle, Sonoma County, Calif.
11. Franciscan (coastal belt) graywacke (59-119) from ridge 7,000 ft N. 62° E. of Reese Gap, Skaggs Springs quadrangle, Sonoma County, Calif.
12. Franciscan (coastal belt) graywacke (59-308) in canyon of Wheatfield Fork of Gualala River at north boundary of Tombs Creek quadrangle, Sonomo County, Calif.
13. Franciscan graywacke (80-RGC-58-1), 4,000 ft N. 25° W. of Blunt Point Lighthouse, Angel Island, Marin County, Calif. By rapid rock analysis method. Analysis by P. L. D. Elmore, S. D. Botts, I. H. Barlow, and M. D. Mack.
14. Franciscan graywacke, Quarry Point, Angel Island, Marin County, Calif. (Bloxam, 1960, p. 559). Analysis by T. W. Bloxam.

15-21. By rapid rock analysis method described in U. S. Geol. Survey Bull. 1036-C. Analyses by P. L. D. Elmore, S. D. Botts, I. H. Barlow, and Gillison Chloe.

15. Schistose graywacke (S-39-A), on shore 750 ft southeast of Campbell Point, Angel Island, Marin County, Calif.
16. Franciscan graywacke (SF-373) near sea level 3,350 ft east of Lands End, San Francisco North quadrangle, San Francisco, Calif.
17. Franciscan graywacke (SF-2114), west side U. S. Highway 101, at a point 5,050 ft northwest of lighthouse at Lime Point, San Francisco North quadrangle, Marin County, Calif.
18. Arkosic graywacke (SF-2122), Franciscan(?), quarry 4,100 ft east from "peak 1314," San Bruno Mountain, San Francisco South quadrangle, San Mateo County, Calif.
19. Franciscan volcanic graywacke (SF-2140), north side of intersection of Masonic and Roosevelt Aves., San Francisco, Calif.
20. Franciscan graywacke (SF-2141), east side of Laguna Honda, San Francisco, Calif.
21. Franciscan graywacke (SF-2148), 200 ft west of Kearny Street and 50 ft south of Francisco Street, Telegraph Hill, San Francisco, Calif.

[a] Total of original analysis which reports all oxides to 0.01.
[b] Also contains BaO 0.04, ZrO_2 0.05, and SO_3 0.15.
[c] Also contains ZrO_2 0.04.

Figure 7. Location of analyzed graywackes listed in table 1.

weight percent of the oxides to equivalent molecular proportions by dividing by the molecular weight of a single-cation oxide: e.g., for SiO_2 one simply divides by the molecular weight of silica, but for Al_2O_3 one divides by the molecular weight of $AlO_{3/2}$, etc. (In this step one may also multiply each component by 1,000 to eliminate decimals.) All the hydrogen of combined water is considered to be in the form of (OH) ions in the rock, so it, as well as other rarer constituents such as F and Cl, are regarded as anions and therefore not included. When the equivalent molecular proportions of the cations have been obtained, they are summed, and each is divided by the sum, thus yielding the percent of each cation in a unit volume and in a total of 100 cations. These cations can then be readily combined to form various minerals, and a systematic procedure for making the combination to yield a standard "catanorm" is given by Barth (1955). Because the cations are made initially to total 100 percent, the minerals made into an assemblage that utilizes all the cations will also total 100 percent. This method of recasting an analysis into normative minerals is appreciably faster than the C.I.P.W. method, but its greatest advantage is the ease with which the cation proportions can be recast into the different normative mineral assemblages that most closely approximate the actual mineral assemblages of different analyzed rocks. The final results are usually expressed, as they are in this report, as molecular norms, which differ only slightly from weight norms and are equally suitable for construction of the various types of diagrams used to compare some, or all, of the components of analyzed rocks.

The standard catanorms calculated from the graywacke analyses are useful for comparative purposes, but, because they are designed to represent the mineral assemblages that might result from the cooling of a magma of the same composition, they do not give a proper picture of the mineral components actually present in the graywacke. For example, nearly

Table 2. Comparison of Franciscan graywackes with other graywackes.

	1	2	3	4	5	6
SiO_2	67.5	64.2	64.7	68.1	71.1	69.7
TiO_2	0.5	0.5	0.5	0.7	0.5	0.6
Al_2O_3	13.5	14.1	14.8	15.4	13.9	14.3
Fe_2O_3	1.2	1.0	1.5	1.0	tr	1.0
FeO	3.0	4.2	3.9	3.4	2.7	2.5
MnO	0.1	0.1	0.1	0.2	0.05	0.1
MgO	2.2	2.9	2.2	1.8	1.3	1.2
CaO	2.4	3.5	3.1	2.3	1.8	1.9
Na_2O	3.6	3.4	3.1	2.6	3.7	3.5
K_2O	1.7	2.0	1.9	2.2	2.3	2.4
H_2O+	2.5	2.1	2.4	2.1	1.9	1.9
H_2O-	0.4	0.1	0.7		0.26	0.4
CO_2	0.8	1.6	1.3	--	0.12	0.1
P_2O_5	0.1	0.1	0.2	0.2	0.1	0.2
Total	99.5	99.8	100.4	100.0	99.8	99.9
MOLECULAR NORM-CATANORM						
Q	31.3	25.7	30.1	34.3	32.4	32.7
or	10.6	12.0	11.5	13.5	14.0	14.5
ab	33.8	31.5	29.0	24.5	34.5	33.0
an	6.2	6.5	6.0	10.5	7.5	8.0
C	4.0	4.6	6.3	5.7	3.0	3.5
en	6.3	8.2	6.4	5.2	3.6	3.4
fs	3.1	5.4	4.6	3.6	3.8	2.2
mt	1.3	1.0	1.6	1.2	--	1.2
il	0.8	0.6	0.6	1.0	0.6	1.0
ap	0.4	0.3	0.5	0.5	0.3	0.5
cc	2.0	4.2	3.4		0.2	0.2
MOLECULAR NORM—MAKING USE OF COMBINED WATER						
Q	31.5	28.2	30.3	35.4	31.1	31.4
or	3.5	1.5		--	13.0	11.5
plag	40.0	40.0	35.0	35.0	42.0	41.0
chl	7.9	11.4	9.1	7.4	6.1	4.6
kaol	2.4		3.4	0.6	5.2	4.6
ms	9.8	14.7	16.1	18.9	1.4	4.2
mt	1.3	1.0	1.6	1.2		1.2
il	0.8	0.6	0.6	1.0	0.6	1.0
ap	0.4	0.3	0.5	0.5	0.3	0.5
cc	2.0	4.2	3.4	--	0.2	0.2
% An in plag	15.5	16.2	17.1	30.0	17.8	19.5

1. Average of 21 Franciscan graywackes included in table 1 of this report.
2. Average graywacke (Pettijohn, 1949, p. 250).
3. Average of 23 graywackes (Pettijohn, 1957 p. 307). Omitted from analysis and total is SO_3 of 0.04.
4. Average of 30 graywackes (Tyrrell, 1933, p. 26). Fe_2O_3 modified to give correct summation.
5. Composite of 20 Wellington graywackes, New Zealand (Reed, 1957, p. 22).
6. Average of 14 New Zealand lower Mesozoic "Alpine" graywackes (Reed, 1957, p. 22)

Figure 8. Ternary diagram showing normative quartz, feldspar, and "rest" in 24 Franciscan graywackes.

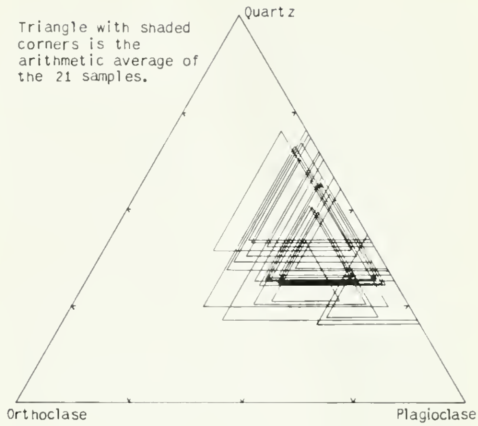


Figure 9. Ternary diagram showing normative quartz, orthoclase, plagioclase, and "rest" in 21 Franciscan graywackes.

all of the molecular norms contain corundum (C), which does not mean the sediments contain corundum but instead indicates an excess of alumina over that required to form feldspars from the alkalies. In addition, all of the analyses show normative orthoclase, yet staining of the samples has indicated that the potassium in most is not present in feldspar but rather, in such minerals as muscovite, celadonite, or a K-bearing clay mineral.

To give a closer approximation of the mineral composition of the graywackes, we have calculated the other molecular norms shown on tables 1 and 2 using a theoretical chlorite [3(Mg,Fe)·2Si·4(OH)] muscovite [K·3Al·3Si·2(OH)], and kaolinite [Al·Si·2(OH)]. To form these hydrous or (OH)-bearing minerals requires the use of the water, which is not used in calculating the standard catanorm; but, making use of the water permits one to establish a balance between muscovite, orthoclase, and kaolinite. The resultant molecular norm is a better approximation of the actual mineral content of the graywacke, but as no K is assigned to celadonite, illite, or other K-bearing clay, there is too much normative muscovite, or in some cases, too much orthoclase.

The molecular norms calculated by this method have been used to construct two ternary diagrams, figures 8 and 9, which serve to give a visual impression of the components and variations in Franciscan graywacke.

Figure 8, on which the corners are quartz, total feldspar, and "rest," indicates the ratio of quartz to total feldspar, including the feldspar in rock fragments as well as in monomineralic grains, ranges from 3:2 to 1:3. It also shows the mafic components range from 10 to 32 percent, although the inclusion of 13.6 percent calcite with the "rest" of one of the samples makes it appear to have 44 percent mafics. Other norms and modes gleaned from the literature are also shown in the diagram.

Figure 9, with corners of quartz, orthoclase, and plagioclase, shows each sample as a triangle, with the side opposite a corner indicating the percent of that corner component. As the values used for quartz, orthoclase, and plagioclase are true percents, rather than recalculated so as to add to 100 percent, the size of the triangle indicates the amount of other components. The range in quantity of each of the apex components can be read from the diagram, and it is interesting that there is no apparent trend toward a change in the mafic, or "rest," component with a change in any of the other three main components.

As these diagrams are almost entirely based on recalculation of analyses they may not accurately represent the exact mineral composition of any of the rocks, but, owing to the difficulties of making precise point counts of sections, or grain counts based on mineral separations, the results may be as accurate as modal analyses. In any event, they show well the range in mineral composition present in the Franciscan graywackes.

Origin. In summary, graywackes of the Franciscan eugeosynclinal assemblage are similar in texture and composition to orogenic, eugeosynclinal deposits found in other parts of the world. The vast volume of terrigenous material, as well as the great thickness locally of individual beds and the presence of a high matrix-content, points to a very rapid deposition or

"pouring-in" of the sedimentary material. The absence of interlayered limestone or calcareous cement in most of the Franciscan also suggests continuous and rapid deposition. Lack of rounded quartz and feldspar grains, as well as the high percentage of labile rock fragments, indicates rapid mechanical erosion of a nearby source area. The low Fe_2O_3/FeO ratio and paucity of interlayered clay beds also indicate the lack of chemical weathering in the source area. Apparently marine conditions prevailed throughout the deposition of Franciscan rocks, and, although graded beds and sole markings are not commonly seen, the sandstone textures, the lack of large-scale crossbedding and ripple marks, as well as the absence of an indigenous shelly fauna, point to turbidity current and fluxo-turbidity current deposition in a deepwater environment (Dzulynski and others, 1959). A few scattered observations show a general north-south orientation of current-produced sole markings, but reliable observations showing current direction are so few that no conclusion regarding direction of source should be made now on this basis.

The nature of the source area from which the Franciscan sediments were derived is imperfectly understood. The lithic fragments indicate a mixed crystalline and sedimentary terrane, and the presence locally of volcanic-rich graywacke and tuffaceous beds points to a volcanic source for some of the sediments. Much of the latter material, however, may have been derived from penecontemporaneous, intra-Franciscan volcanism.

The Franciscan graywacke is similar to other graywackes in having a K_2O/Na_2O ratio of less than 1.0 (Pettijohn, 1957; Middleton, 1960, p. 1017), and in having albite as the dominant feldspar. The reason for the low K_2O/Na_2O ratio, both in the Franciscan and other similar units, is not understood, but Middleton (1960, p. 1017, 1018) has suggested the three following possible explanations:

1. Soda-rich source rocks. Alkaline granite, quartz diorite, granodiorite, andesite, basalt, spilite, and granite gneiss would provide a ratio of less than 1.0.
2. Regional soda metamorphism. Little support is given to this idea because of the lack of petrographic evidence pointing to this mechanism.
3. Incomplete weathering of source rocks. Little favor is given this concept because K-feldspars are more resistant to normal weathering than are plagioclase feldspars, and Na_2O is removed from rocks during weathering at least as rapidly, and commonly more rapidly, than K_2O.

To this list should also be added the possibility of derivation either from a suite of older eugeosynclinal rocks with similar characteristics, or from their metamorphosed equivalents.

Middleton (1960, p. 1018) concludes that "* * * the peculiar characteristics of high-rank graywackes are a result of a partial volcanic (spilitic) provenance, combined with rapid erosion and little chemical weathering." This statement is obviously applicable to the Franciscan graywackes, but certainly does not explain fully their anomalous composition.

Alteration. Much of the Franciscan graywacke has not been appreciably altered or sufficiently metamorphosed for it to contain discernible new minerals or to have developed schistosity. In some areas, however, the graywacke has been subjected to various kinds of alteration, more drastic than those that can be attributed to diagenesis. One cannot always be sure what kind of alteration is involved, and some of the most carefully studied changes have been ascribed to different types of metamorphism or alteration by different geologists. However, there is general agreement that regional or load metamorphism, contact metamorphism, pneumatolytic alteration, and hydrothermal alteration have each affected the graywackes in certain local areas. The most widespread alteration of the graywacke is the result of regional or load metamorphism, but, as this type of metamorphism also affects the other rocks of the assemblage, it is discussed at considerable length under the separate heading of *Metamorphic rocks.* In this part of the text, some metagraywackes formed by regional metamorphism are mentioned briefly because they resemble the unaltered graywacke so closely that their metamorphic character may not be recognized; however, the main discussion here will deal with the alterations brought about by processes that are more local.

Regional metamorphism of Franciscan graywacke under conditions of only static load and deep burial may result in the formation of nonschistose rocks, which superficially appear unmetamorphosed but are properly assigned to either the zeolite or blueschist metamorphic facies. Graywackes that should be assigned to the zeolite facies can generally be recognized by the presence of white, sugary veins of laumontite. Graywackes that have been subjected to blueschist facies metamorphism may contain either jadeite or glaucophane, depending on how soda released by the breakdown of plagioclase has been recombined. Metagraywackes containing glaucophane are normally recognizable because even a little glaucophone gives the rocks a bluish cast, but unsheared graywackes that are extensively jadeitized are not readily recognized. They are, however, heavier than normal graywacke, and we have found that all graywackes with a specific gravity greater than 2.70 contain metamorphic minerals and are really metagraywackes.

Graywacke altered by contact metamorphism is rare, as are situations where one might expect this kind of alteration. Virtually no granitic rocks intrude the Franciscan graywacke, intrusive Franciscan mafic rocks are uncommon, as are more acid Tertiary intrusives, and apparently most of the ultramafic masses were injected plastically as serpentine at temperatures far below their melting point. However, Chesterman (1960) has carefully described graywacke at Leech Lake Mountain (Covelo quadrangle) in which new minerals are formed by contact metamorphism along the margins of serpentinized peridotite sills. He found that in the graywacke within a foot of the ultramafic

intrusive diopside-jadeite is abundant, and mafic rock fragments have been destroyed; at about a foot from the contact the pyroxene is aegirine and minor blue amphibole is present. Three feet from the contact glaucophane has given way to actinolite, and 15 feet from the contact a blue-green hornblende is present. In this area other graywacke engulfed in the peridotite has been converted to rodingite containing a diopside-jadeite-acmite pyroxene. The development of a little blue amphibole in the contact rocks is of particular interest, as many geologists have attributed the orgin of the glaucophane schists of the Coast Ranges to metamorphism that is related to mafic and ultramafic intrusives, though they also generally suggest that the process is pneumatolytic and involves the introduction of material.

Pneumatolytic alteration of graywacke, involving introduction or loss of elements, may be difficult to distinguish from regional metamorphism, in which there is often some limited migration of elements but no overall change in the chemical composition of the entire rock mass. The formation of glaucophane schists has been attributed by Taliaferro (1943b, p. 175) and others to pneumatolytic alteration, but it is the writers' belief that analyses generally indicate these schists are comparable in chemical composition to the rocks from which they were derived (table 14a and b). These glaucophane-bearing metagraywackes and schists are therefore treated as products of isochemical reactions in the later section on metamorphic rocks. Veins of quartz, calcite, albite, and adularia occur rather commonly in the Franciscan graywackes, and they too have been cited as evidence of pneumatolytic alteration. However, these veins can be equally well explained as resulting from local solution of minerals in the graywacke, and they may provide one of the earliest indications of load metamorphism. The veins are most common in areas containing some metamorphic rocks but are more widespread than the limits of regionally metamorphosed graywacke now recognized. Unfortunately, no one has yet systematically mapped their distribution even throughout the extent of a single 15-minute quadrangle. Though pneumatolytic alteration appears to us to be uncommon, some unusual Franciscan rocks have unquestionably been enriched in boron. The most striking examples are tourmalinized graywackes at the East Peak of Mount Tamalpais, in Marin County, mentioned by Rice (1960). In the most altered graywacke, tourmaline amounts to more than 50 percent, and adularia is also a major constituent. As the rocks are vuggy, they are believed by Rice to have been altered when at shallow depth. Another boron-bearing silicate, axinite, has been found in veins with prehnite a few miles farther west at Stinson Ranch. Axinite veinlets also are reported to occur in the Trout Creek manganese mine ores, Black Rock Mountain quadrangle, Trinity County (Hewett and others, 1961, p. 58). In none of these areas is there any nearby intrusive igneous rock that can be regarded as the source of the boron.

Hydrothermal alteration has modified Franciscan graywacke over areas ranging in size from a few square feet to nearly a square mile (Bailey, 1946, p. 214; Yates and Hilpert, 1945, p. 22, 1946, p. 253). Most of the larger areas of alteration are in the vicinity of mercury deposits, but some that are obviously related to Tertiary volcanism contain no known mercury minerals, and still other, generally small, areas can be related only to fault zones. In the Eastern Mayacmas mercury district, Lake and Napa Counties, hydrothermally altered graywacke is widespread and particularly well developed near the Oat Hill mine. In the Western Mayacmas district altered graywacke occurs about some of the mercury mines, but the alteration is considerably more pronounced along a zone of more recent hydrothermal activity that includes The Geysers and the Little Geysers but contains only minor amounts of mercury. In Lake County hydrothermally altered graywacke is prominent along a fault that extends from Bartlett Springs northwest to Crabtree Hot Springs in Lake Pillsbury quadrangle. The alteration seems to have been most intense near Bartlett Springs, but only at Crabtree Hot Springs has a little quicksilver and arsenic mineralization been noted (Fairbanks, 1893b, p. 61).

Areas of hydrothermal alteration can generally be recognized readily, because the alteration leads to a bleaching of the graywacke, and also, in most areas, to the developmenr of closely spaced veinlets of quartz, ferroan dolomite, calcite, or siliceous limonite. The bleaching of the rocks is a result of removal of iron, which may go into a carbonate, or an oxide, or combine with sulfur to form pyrite. A more subtle and more pervasive change is the alteration of the feldspars to clay minerals, and, in the most extreme alteration, quartz is lost so that the final product is largely clay. The particular clay mineral formed is different from place to place, but the clays from only a few areas have been adequately studied. Pre-1950 reports refer to kaolin or kaolinitization, but because these minerals were identified without benefit of X-ray techniques, they probably should be discounted. We found that greasy graywacke from the Culver-Baer mine, Sonoma County, consisted largely of montmorillonite, with minor kaolinite and chlorite. Julius Schlocker (oral communication, March 1961) found that in the San Francisco area some graywackes have been completely altered to kaolinite group minerals, others contain abundant montmorillonite, and in still others the end product is a chlorite rock, or a mixture of chlorite, random layered chlorite and mica, and talc. He also found that pyrite is generally formed as a result of hydrothermal alteration. D. E. White (oral communication, March 1961) reports yet a different type of hydrothermal alteration at the Sulphur Bank mine, Lake County, where clays are absent below the water table, but where an ammonium-bearing mineral, apparently a feldspar [1] or zeolite, has replaced the origi-

[1] A new mineral, named buddingtonite; see Erd, R.C., and others: Am. Mineralogist, v. 49, p. 831-850.

nal plagioclase of the graywacke. In The Geysers area, in eastern Sonoma County, J. R. McNitt (written communication, 1961) found acid leaching in the oxidation zone converted Franciscan graywacke into a porous mass of alunite, opal, and residual quartz; below the oxidation zone the hydrothermal alteration of the graywacke resulted in the formation of pyrite, the growth of sericite in the groundmass and feldspar grains, and the deposition of calcite and quartz in fractures. Both kaolinite and dickite were identified in muds thrown from the steam wells.

Shale

Shale, including siltstone, probably amounts to about 10 percent of the Franciscan sedimentary rocks. It has been so little studied that no definitive description is now possible nor is the relative abundance of siltstone and claystone known. It is obvious, however, that there are two unlike and readily distinguishable varieties of shale—a dark-gray to black variety occurring chiefly interbedded with graywacke, and a red or green ferruginous variety occurring interbedded with chert. Because the latter is restricted in its distribution and clearly has an origin closely related to that of the chert, it is discussed in this report along with the cherts and is omitted from the following description.

Occurrence and megascopic features. The Franciscan shale, though generally dark gray or black, is in some places a grayish tan or even olive color, and these rocks tend to weather to still lighter shades. However, weathered shale usually is not seen in outcrop because of soil cover, and natural exposures that are predominantly shale are uncommon. Shale is best seen where it forms thin seams between much thicker layers of graywacke, but locally it forms units a few feet thick. Sections of still greater thickness with only a few interbeds of graywacke are unusual in the Franciscan, but some beds as much as 500 feet thick have been reported. Where shale is especially abundant it forms a zone of structural weakness that is readily crumpled and sheared, and in many roadcuts what may once have been sections of shale a few hundred feet thick are now seen to be so disturbed that no estimate of initial thickness is possible. Widespread shearing may also partly account for the general absence of graded bedding, which seems to be common only in the somewhat unusual, graywacke-shale sequence east of Mount Hamilton.

The shales are normally fissile and dull in luster, but in some areas they are phyllitic and shiny, apparently because of an increase in the size of micas. Although the shales are highly folded in many places, slaty cleavage has been observed only in western Tehama County in an area where the graywacke has been converted to a semischist.

Microscopic features. Mineralogically the Franciscan shales seem to be quite similar to the graywackes, with a high proportion of angular mineral or rock fragments and only a small amount of clay minerals. The mineral grains that can be identified in

Table 3. Analyses of shales accompanying graywackes in the Franciscan.

	1	2	3	4	5	6
SiO_2	62.54	63.2	60.0	67.1	63.2	58.51
TiO_2	0.87	0.68	0.73	0.55	0.71	0.66
Al_2O_3	14.81	16.1	18.1	13.6	15.7	15.55
Fe_2O_3	2.02	0.7	1.0	1.3	1.3	4.03
FeO	5.47	4.9	5.0	3.5	4.7	2.50
MnO	0.05	0.09	0.11	0.06	0.08	tr
MgO	3.38	3.1	2.9	2.4	3.0	2.44
CaO	1.40	1.1	1.1	2.6	1.5	2.99
Na_2O	2.90	2.4	1.8	1.4	2.1	1.28
K_2O	2.13	2.5	3.2	2.0	2.4	3.28
H_2O+	2.91	3.7	4.4	4.0	3.7	3.69
H_2O-	0.82	0.49	0.64	0.10	0.52	1.31
CO_2	0.08	--	0.10	--	0.04	2.51
P_2O_5	0.15	0.20	0.17	0.19	0.18	0.17
S	0.05	0.22	0.34	0.39	0.25	0.22
Organic	0.96	--	--	--	--	--
Subtotal	100.54	99.4	99.6	99.3	99.4	99.14
Less O=S	0.03	0.11	0.17	0.19	0.13	0.11
Total	100.51	99.3	99.4	99.1	99.3	99.03
Molecular norm-catanorm						
Q	26.3	29.6	27.6	41.2	31.2	35.2
or	13.5	15.5	20.5	12.5	15.5	21.0
ab	27.5	23.0	17.5	13.5	20.4	12.5
an	6.0	4.5	4.5	12.5	6.9	--
C	6.5	9.2	11.8	5.8	8.3	11.6
en	9.8	9.2	8.6	7.2	8.7	6.6
fs	6.4	6.2	6.0	3.4	5.5	--
mt	2.2	0.7	1.2	1.5	1.4	4.2
il	1.2	1.0	1.0	0.8	1.0	1.0
hm	--	--	--	--	--	0.2
py	--	0.6	0.9	1.0	0.6	0.6
ap	0.3	0.5	0.3	0.5	0.4	0.3
cc	0.2	--	0.2	--	0.1	6.0
$MgCO_3$	--	--	--	--	--	0.8
Molecular norm-using combined water						
Q	27.9	29.3	26.5	42.1	31.5	33.1
plag	33.5	27.5	22.0	26.0	27.2	12.5
musc	18.9	21.7	28.7	17.5	21.7	29.4
kaol	2.2	6.0	7.2	1.6	4.2	6.4
chl	13.5	12.6	12.1	8.9	11.8	5.5
mt	2.2	0.8	1.2	1.5	1.4	4.2
il	1.2	1.0	1.0	0.8	1.0	1.0
hm	--	--	--	--	--	0.2
py	--	0.6	0.9	1.0	0.6	0.6
ap	0.3	0.5	0.3	0.5	0.4	0.3
cc	0.2	--	0.2	--	0.1	6.0
$MgCO_3$	--	--	--	--	--	0.8

1. Franciscan black siltstone (NA-315) from Fern Hill, New Almaden district, Santa Clara County, Calif. Analysis by Mrs. A. C. Vlisidis, U.S Geological Survey.

2-4. By rapid rock analysis method described in U.S. Geol. Survey Bull 1036-C. Analyses by P. L. D. Elmore, S. D. Botts, I. H. Barlow, and Gillison Chloe.

2. Franciscan siltstone (SF-1140) from North Broadway Tunnel at a point 150 ft east of center line of Jones Street, San Francisco, Calif.

3. Franciscan shale (SF-2126) from quarry 1200 ft NW of Point San Pedro, San Quentin quadrangle, Marin County, Calif.

4. Franciscan metashale, south side of State Highway 152 at B.M. 950, 2,800 ft W. of east edge of Pacheco Peak quadrangle, Santa Clara County, Calif.

5. Average of 1-4.

6. Average of 78 shales (Clarke, 1924, p. 631). Not included are 0.05 BaO and 0.81 C.

thin section are the same as those in the graywacke, being chiefly quartz and feldspar, and fine-grained chlorite and sericite. The principal clay-size constituents were determined by X-ray on about two dozen samples from the San Francisco area by J. Schlocker. He reports (oral communication, 1963) that in the gray, green, or black shales mica generally predominates, chlorite is normally also abundant, and kaolinite is either absent or very minor. Both the mica and chlorite may contain some expandable layers. In tan shales, which are presumed to be weathered, mixed-layer mica-montmorillonite or vermiculite predominates and may amount to as much as 90 percent of the fine fraction. Although the fresh shales are dark in color, the organic content is probably low except in those varieties showing obvious carbonized plant remains. Authigenic pyrite is rarely found. Uncommonly the shales are calcareous, and limestone nodules have been found in only a few places. Unusual phosphatic nodules were found in shales in San Francisco by Julius Schlocker (oral communication, 1962).

Chemical features. Chemical analyses of four Franciscan shales are shown in table 3, along with their average and an average of 78 other shales for comparison. Both anhydrous and hydrous norms for these are included, as it is often more convenient to compare normative minerals than oxide percents. These Franciscan shales differ from the given average shale in that they contain more silica, have a smaller potash to soda ratio, and have a ferric to ferrous iron ratio that is not only smaller but generally less than 1. In these respects Franciscan shales are more like the average Franciscan graywacke (see table 1, and fig. 14). It is interesting that in the standard catanorm all the shale samples have considerable orthoclase, but in contrast to the graywackes, all the normative orthoclase can be converted to muscovite if the combined water is used in forming a normative mineral assemblage. This is partly the result of the shales containing more combined water, but it results chiefly from their containing somewhat more alumina, which is also shown by the larger amount of corundum (C) in the standard catanorm.

Conglomerate

Conglomerates are invariably reported to be "rare" or "uncommon" in the assemblage of Franciscan rocks, but they are so widespread that they were noted in nearly every 15-minute quadrangle in which Franciscan rocks have been mapped. Their typical occurrence is as lenses a few tens of feet thick and exposed over lengths of a few hundred feet or less; however, the largest exposure reported is a lens 2,000 feet long and 75 feet thick in the section west of Mount Hamilton. Because the conglomerate is so limited in extent, none of the maps referred to in this study shows it with a separate lithologic symbol.

The matrix of the conglomerate is everywhere graywacke and is generally regarded to be the same as in the enclosing graywacke beds. The largest boulders reported have a maximum dimension of 2½ feet; the average size of the clasts is between 1 and 4 inches. No general trend toward an increase in either the average or maximum size of pebbles or boulders, either across or along the area of deposition, is apparent to us, although Taliaferro (1943a, p. 140, 143) stressed a westward coarsening as indicating derivation from a landmass to the west.

The clasts of the conglomerate can be conveniently grouped, as shown in figure 10, into one of two categories: (1) lithic types that were not formed originally as part of the Franciscan and must have been brought into the depositional area, and (2) lithic types that are present in the Franciscan and thus indicate either cannibalism of previously deposited Franciscan rocks or introduction of similar foreign rocks. Included in the first category are quartzite, black chert, and various quartz and feldspar porphyries which form a prominent part of most of the Franciscan conglomerates. Granite, quartz-diorite, and granitic rocks of intermediate composition also are assigned to the first category, because the Franciscan is not known to be intruded by granite. In the second category are included graywacke, shale, red and green chert, mafic volcanic rocks, and glaucophane schist. It will be noted in figure 10 that most conglomerates in the area south of Sebastopol contain some of these possibly intraformational rocks along with rocks of the first category, but a few Franciscan conglomerates, such as those of the Tesla quadrangle, consist entirely of rocks that could have an intraformational source. It is perhaps also significant that the areas containing conglomerates with clasts of possible intraformational origin are also the areas containing granitic pebbles and boulders.

Only unusually hard and resistant varieties of rocks comprise the clasts that must have an extraformational source, and they are invariably well rounded and in places polished. In contrast, several of the rocks of possible intraformational origin, such as the graywackes and shales which are relatively easily broken and abraded, commonly also occur as subrounded to angular fragments. The extraformational clasts have obviously been abraded much more than those of possible intraformational origin. The extraformational clasts have been transported in streams or rivers for at least tens of miles, or traveled shorter distances and become stagnant along a shoreline where they were subject to wave action, or are second generation pebbles reworked from older conglomerates. Conversely, the pebbles of possible intraformational origin have not received such intense abrasion. The origin of conglomerates composed only of the hard extraformational pebbles can be readily explained by several hypotheses, but that of conglomerates composed

Location	Maximum size in inches	Range or average size in inches	Extra-formational									Possibly intra-formational							
			Granite	Quartz diorite	Quartz porphyry	Felsic volcanics	Limestone	Arkose	Quartzite	Black chert	Vein quartz	Mafic volcanics	Colored chert	Graywacke	Shale	Conglomerate	Glaucophane schist	Schist	Serpentine
1. Blue Lake quadrangle		½-1	X		▒		X		▒	▒	X	X							
2. Lower Lake quadrangle	10									X	X	▒	X	X	X				
3. Western Mayacmas district	6				▒	▒			▒	▒		X	X	X					
4. Eastern Mayacmas district	6				▒				▒	▒									
5. Healdsburg quadrangle	6	1-6			▒						X	X							
6. Sebastopol quadrangle	<10				▒				▒	▒		X							
7. North of San Francisco Bay		>6		▒	▒				▒	▒	▒		▒	▒				▒	
8. Angel Island	12	2½			X	X		▒	▒	▒		X	▒	▒	X				
9. Mount Diablo	12	2							▒	▒		▒			X				
10. Belmont, San Mateo quadrangle	24	1½		▒				▒	▒	▒			▒	▒	X		X		
11. Montara Mtn. quadrangle										▒									
12. Pleasanton area, Livermore quadrangle			▒						▒	▒		▒							
13. Tesla quadrangle	4	<1											▒	▒	▒				
14. San Jose-Mount Hamilton quadrangle	10		▒	▒	▒				▒	▒	X			▒					
15. East half of Mount Hamilton quadrangle	12		▒	X	▒								▒	▒	▒		X	X	X
16. Mount Boardman quadrangle	18		X	X	▒		X		▒	▒	X			X	X		X	X	
17. New Almaden district	9	2			▒	▒		X	▒	▒	X	▒		▒	X	X			
18. San Juan Bautista quadrangle									▒										
19. Quien Sabe quadrangle	30	½-2	▒		▒				▒	▒	▒		▒	▒		▒			
20. San Benito quadrangle	18	2-3			▒				▒	▒				X					
21. Priest Valley quadrangle	18												▒						
22. Cape San Martin quadrangle				X			X		▒			X	X				X		
23. Cape San Martin quadrangle	8	1		X	X							X		▒	X				
24. San Simeon quadrangle	16	5	▒		X				X	X				X					
25. San Luis Obispo quadrangle			▒						▒				▒				X		
26. San Benito Island, Baja California									▒	▒		▒							

▒ = >5 percent, "abundant" or "common" X = <5 percent, "less common" or "rare"

1. Manning, G. A., and Ogle, B. A. (1950, p. 20)
2. Brice, J. C. (1953, p. 13-14)
3. Bailey, E. H. (1946, p. 205)
4. Yates, R. G., and Hilpert, L. S. (1946, p. 236)
5. Gealey, W. K. (1951, p. 12)
6. Travis, R. B. (1952, p. 14)
7. Weaver, C. E. (1949a, p. 22; 1949b, p. 17)
8. Schlocker, Julius (oral communication, 1960)
9. Pampeyan, E. H. (oral communication, 1960)
10. Schlocker, Julius (oral communication, 1960)
11. Darrow, R. L. (1951)
12. Hall, C. A. (1958, p. 4)
13. Huey, A. S. (1948, p. 18)
14. Crittenden, M. D., Jr. (1951, p. 18)
15. Soliman, S. M. (1958)
16. Maddock, M. E. (1955)
17. Bailey, E. H. (in press)
18. Allen, J. E. (1946, p. 26)
19. Leith, C. J. (1949, p. 14)
20. Wilson, I. F. (1943, p. 196)
21. Taliaferro, N. L. (1943a, p. 142)
22. Bell, G. L. (1939)
23. Taliaferro, N. L. (1943a, p. 142)
24. Taliaferro, N. L. (1943a, p. 141)
25. Fairbanks, H. W. (1904, p. 2)
26. van West, Olaf (1958)

Figure 10. Rocks in Franciscan conglomerates.

of these and intraformational rocks are more restricted as to possible origin.

The conglomerates provide clues to the origin and depositional environment of the Franciscan assemblage of rocks even though they form a very minor part of the entire unit. The anomaly presented by the conglomerates composed of pebbles of mixed origin has been pointed out; other unusual features of the con-

glomerates are: (1) their very rare occurrence, both in time and space, yet widespread distribution, (2) their coarseness, especially as related to the small size of the conglomerate lenses, and (3) the unsorted or unwashed character of their matrix. The last two of these features are readily explained by postulating that the conglomerates were moved to their position by density currents moving normally to the axis of the basin. Mixed conglomerates might be expected in areas where the margin of the basin was uplifted to form a shoreline subject to wave action near the mouth of a river carrying extraformational rocks. Whatever the origin of the conglomerates, they represent an unusual event happening infrequently and at widely spaced localities, but repeated many times during the depositional period.

The presence of quartzite, black chert, and porphyries has been pointed to as an indication of a western source by Taliaferro (1943a, p. 143). We believe that the quartzite and black chert might well have been derived from erosion of Paleozoic and lower Mesozoic rocks of the western Sierra Nevada and the Klamath Mountains, or by reworking of pebbles from older formations found in these areas, as, for example, conglomerate of the Bragdon Formation of Mississippian age (Kinkel and others, 1956, p. 40). The porphyries bear some resemblance to the volcanic rocks of Jurassic age in the central Sierra Nevada, although their quartz content seems to be somewhat higher, and they also resemble the Balaklala Rhyolite of Devonian age in the Klamath Mountains (Kinkel and others, 1956, p. 17-32).

Most of the rocks that might be of intraformational origin also might have been derived from erosion of the Paleozoic and lower Mesozoic formations of the Sierra Nevada and Klamath Mountains. However, the source of some which appear on hand lens examination to be nondiagnostic probably could be determined if they were adequately studied in thin section. For example, colored cherts from pre-Franciscan rocks may contain radiolaria that differ from those in Franciscan cherts, and the mineral assemblages of some of the pre-Franciscan metamorphic rocks, if worked out in detail, doubtless will be found to differ from the assemblages found in the Franciscan. Probably the only kind of rock that can be positively identified in the field and confidently interpreted as being derived from erosion of Franciscan terrane is glaucophane schist, which is highly uncommon in the Sierra Nevada and Klamath Mountains, although parts of the South Fork Mountains contain crossite-epidote schist. However, jadeitized graywacke would have the same significance, if it could be recognized.

Glaucophane schists are reported to be present in the conglomerate in the area east of Mount Hamilton (Maddock, 1955; Soliman, 1958), in Belmont and San Carlos (Schlocker, oral communication, 1960), and in the core of Mount Diablo (Davis, 1918b); we have also found these schists in the New Idria diapiric mass and in the massive conglomerate of the "coastal belt rocks" along Buckeye Creek (Hopland quadrangle) in northern Sonoma County. These occurrences seem to offer evidence of intraformational erosion and redeposition of preexisting Franciscan rocks in younger parts of the same unit. Further, considering the overall rarity of glaucophane schist in the Franciscan terrane, it is a reasonable inference that Franciscan conglomerates containing pebbles of glaucophane schist also contain a larger proportion of other intraformational rocks, even though these cannot be so positively identified.

VOLCANIC ROCKS

Occurrence and megascopic features. Volcanic rocks, which probably comprise about 10 percent of the Franciscan eugeosynclinal assemblage, are widespread, but as they are somewhat erratically distributed in space, and probably also in time, the quantity present in any area the size of a 15-minute quadrangle ranges from as little as 1 percent to as much as 30 percent of the Franciscan exposure. Although considerable uncertainty exists regarding the relative ages of the various exposed sequences of Franciscan rocks, the volcanic rocks seem to be least common in an old part of the Franciscan lying east of Mount Hamilton and in the young "coastal belt" of Bailey and Irwin (1959). The relative abundance of volcanic rocks within the Franciscan geosyncline shows no systematic variation from east to west or north to south.

The volcanic rocks clearly include large amounts of both massive and fragmental types, but their original character in many places is difficult to ascertain because of their altered and broken condition. Pillow lavas are common and widely distributed. Although some sequences hundreds of feet thick clearly consist entirely of pillows, the more common exposures of greenstone contain distinguishable pillows only here and there, and the character of the rest of the mass is uncertain. Masses described as flows are generally so regarded simply because they do not show features diagnostic of their true origin. Others described as sills, for example the main "sill" on Angel Island (Ransome, 1894), have been found later to contain pillow structure, suggesting an extrusive origin. Good exposures of pillows can be seen along the west side of U.S. Highway 101, 1½ miles north of the Golden Gate Bridge, at Squaw Rock 5 miles south of Hopland, or in quarries 5 miles south of Willits. Other thick volcanic sequences are largely tuffs or tuff breccias made up of altered mafic glass and fine-grained vesicular basalt and show only crude bedding and sorting. Good examples can be seen along Los Gatos Creek just south of Los Gatos (Los Gatos quadrangle), or near Bodfish Creek in the San Juan Bautista quadrangle (Allen, 1946, p. 23).

Intrusive plugs and dikes must also be numerous enough to have served as feeders for the various widespread volcanic extrusions, but only a few have been recognized. Taliaferro (1943a, p. 147) mentions vent agglomerates occurring along the crest of the Santa Lucia Range in the Cape San Martin quadrangle, and Huey (1948, p. 20) describes volcanic necks in Arroyo Mocho, Tesla quadrangle. The intrusive nature of these masses has been inferred from crosscutting relations and brecciated borders, but such criteria must be applied with caution because similar-appearing greenstone masses with elliptical shapes and brecciated borders occur in shear zones where their form and position result from post-Franciscan tectonic movements.

The volcanic rocks are mafic, and all are at least somewhat altered, so that it is customary to refer to them as greenstones. The kind and degree of alteration is variable and includes zeolitization, low-grade metamorphism of several kinds, spilitization, possible sea-water reaction, and deuteric alteration, in addition to weathering. So widespread are these alterations that it is difficult to obtain for study or analysis a completely unaltered specimen, and it is difficult to isolate the different kinds of alteration that have affected the greenstone.

In spite of variations in degree and kinds of alteration, the outcrops of the volcanic rocks are readily recognized, and some of the varieties such as pillow lavas are resistant enough in many places to form bold outcrops, craggy exposures, or ridges. Others, such as the finer grained tuffs or highly altered and fractured lavas, are no more resistant than the Franciscan graywacke and generally form rounded hills containing few real outcrops. However, the reddish soils developed on them are diagnostic because all of the volcanic

Photo 15 (below). Franciscan pillow lava. East of Black Mountain, Point Reyes quadrangle, Marin County, on Petaluma and Point Reyes road. Note hammer to right and below center for scale.

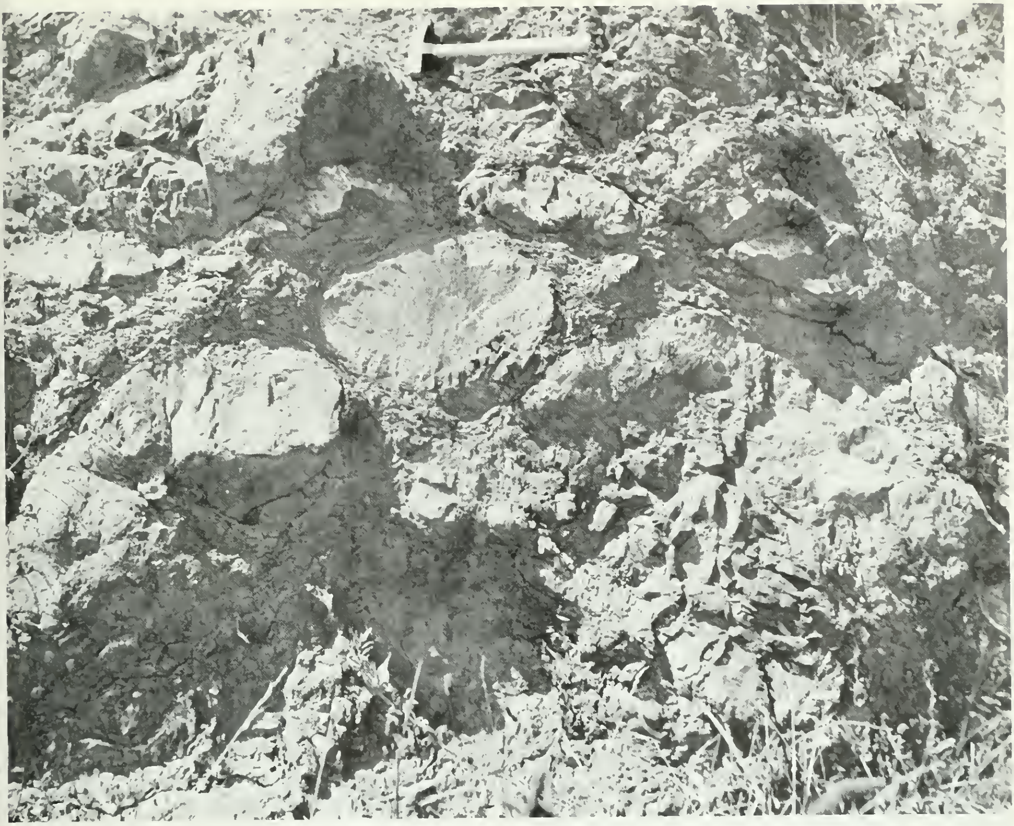


Photo 16 (above). Franciscan pillow lava on U. S. Highway 101 north of Golden Gate bridge. Note abundance of matrix material between pillows.

rocks contain more iron than is found in the surrounding sediments.

The sizes of masses of volcanic rock indicate activity ranging from single isolated extrusions to continued eruption, forming extensive volcanic fields. The thickest accumulation is in the area about St. John Mountain in the Stonyford quadrangle, where a volcanic pile built up to an apparent thickness of 7,000 feet or more. In the Bitterwater Creek area, southwest of Panoche Valley in San Benito County, pillow lavas accumulated to a thickness in excess of 5,000 feet. Another large mass of volcanic rocks, with minor interlayered chert and clastic rock, is found in the Kelseyville quadrangle; it has not been mapped in detail but appears to have a thicknes in excess of 5,000 feet and is exposed over a strike length of nearly 20 miles. In the San Juan Bautista quadrangle, 3,000 feet of agglomerate is overlain by 1,600 feet of rocks described as basalt flows (Allen, 1946). A peninsula bifurcating the eastern part of Clear Lake is made up of volcanic rocks and sediments in a ratio of 9:1 (Brice, 1953, p. 17) with an apparent thickness of 5,000 feet. In many other areas in both the northern and southern Coast Ranges, the volcanic rocks have local thickness in excess of 1,000 feet and are exposed over areas of several square miles. However, only a few volcanic fields seem to have had a length in excess of 10 miles. In dimensions, the volcanic piles are comparable to the seamounts of the Pacific basin described by Menard (1955a), and it seems reasonable to assume that at least the larger piles of Franciscan rocks formed similar structures.

All the extrusive volcanic rocks appear to have been deposited in a submarine environment. Evidence for this type of deposition can be obtained only locally, but there is no contrary evidence indicating subaerial

Photo 17. Small pillow-like masses of greenstone in a matrix of altered glass. Along Rockpile road in the southeastern part of the Ornbaun quadrangle.

deposition. Masses with pillow structure are widespread, and locally these contain limestone or chert with fossil marine microorganisms in the spaces between the pillows. Crudely bedded volcanic breccias, agglomerates, and tuffs are locally interlayered with or grade into graywacke. Features that would indicate subaerial eruption, such as columnar jointing in flows, have not been noted, but as most of the lavas are much fractured, in part by later tectonic activity, it would be difficult to detect any original jointing. Bombs, spherical lapilli, or other structures indicating subaerial deposition have not been found. Tuffs, some even with striking shardlike texture, occur in the Franciscan volcanics, but their limited areal extent relative to their thickness indicates they probably never were airborne. Thus, while there is no reason to believe the volcanic rocks could not have built up to a great enough thickness to have emerged as islands, there seems to be no evidence indicating this happened.

The mode of submarine eruption, and perhaps also the depth of the eruption below sea level (Bailey and McCallien, 1960, p. 368-369), strongly influenced the gross structure of the rock—that is, whether it is massive, in pillows, or in fragments—and the mode of eruption also determined the texture and to some extent the mineralogy and bulk composition of the greenstone. However, owing to the lack of detailed studies, it is not possible to correlate variations in texture, mineralogy, and chemical composition with mode of occurrence or origin in more than a very general way, though such a study would appear to be a fruitful field for further research.

Microscopic features. The greenstones are basaltic, with plagioclase and augite as dominant minerals. The differing development of crystals of these two minerals, either with or without interstitial glass, has yielded a variety of textures. The massive greenstones

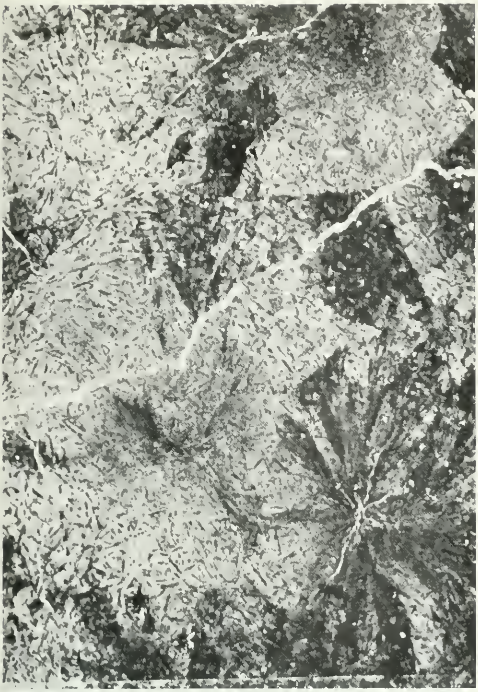


Photo 18 (left). Varialitic greenstone from near margin of a pillow. Radial crystals are pumpellyite with some residual albite. Small dark crystals are composed of a serpentine mineral that has replaced skeletal crystals of olivine. Much larger areas of serpentine replacing well-formed crystals of olivine are also present in the thin section but are not shown in this view. The skeletal crystals show a preferred orientation at right angles to the length of the crystals forming the variole, and thus probably formed later. If the varioles represent crystal growth in a glass, the skeletal olivine crystals also grew in a glass rather than in a magma. Veins contain pumpellyite, chlorite, and calcite. San Francisco North quadrangle (60-807).

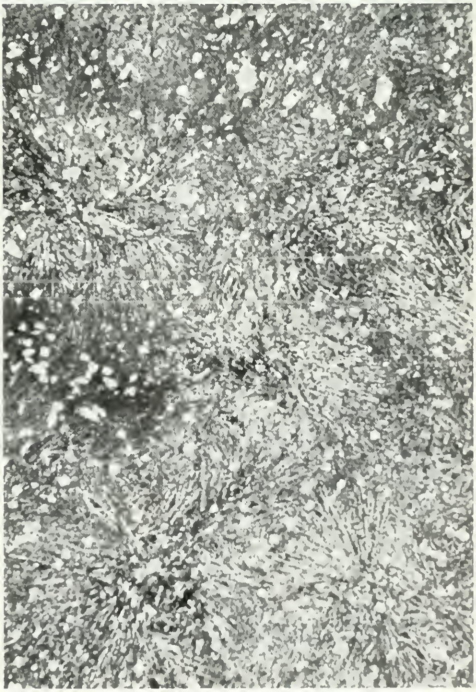


Photo 19 (right). Varialitic greenstone from near center of pillow. Radial groups are pumpellyite and minor albite; light equant crystals are a serpentine mineral replacing olivine. Some fine-grained magnetite is also present. San Francisco North quadrangle (60-805, for analysis see table 5, column 1).

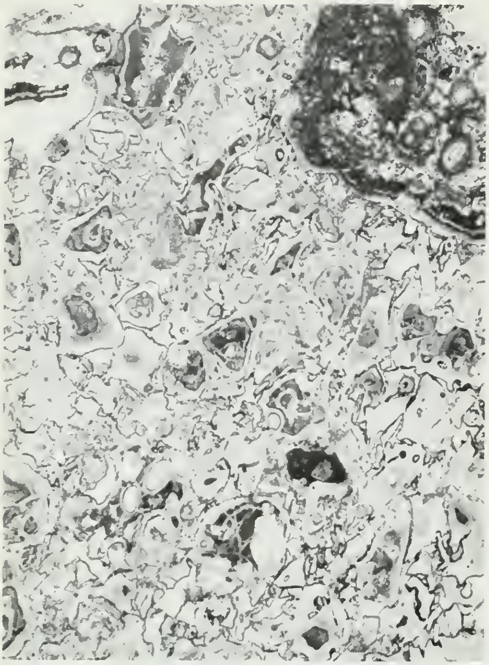


Photo 20 (left). Tuffaceous greenstone composed of fragments of altered basaltic glass in a matrix that probably was once minute fragments of glass. The basaltic glass is now chlorite clouded in many places by minute crystals of pumpellyite. Serpentine minerals replace rare crystals of olivine, but a few crystals of augite are entirely fresh. Albite occurs as crystals in the vesicles and replacing the matrix between altered glass fragments. New Almaden quadrangle (NA 319).

Photo 21 (right). Tuffaceous greenstone composed of fragments of altered basaltic glass, glassy basalt, and sparse crystals of augite. Plagioclase laths in basalt are now albite, and albite also occurs in the vesicles and matrix. Some other primary openings are filled with quartz, and unusually round vesicles are filled by radial aggregates of chlorite. Matrix is largely fine-grained chlorite and pumpellyite, with locally albite or calcite. New Almaden quadrangle (G-1).

Photo 22 (right). Porphyritic greenstone with calcic andesine phenocrysts partly altered to a mixture of kaolinite, pumpellyite, and albite. Groundmass is largely chloritized (?) glass with abundant amygdules, many of which contain one or two varieties of chlorite. Other amygdules contain albite, generally accompanied by pumpellyite, and in a few places by epidote (?). Groundmass glass also contained feldspar laths now altered to aggregates of albite and pumpellyite. Skaggs quadrangle (58-91).

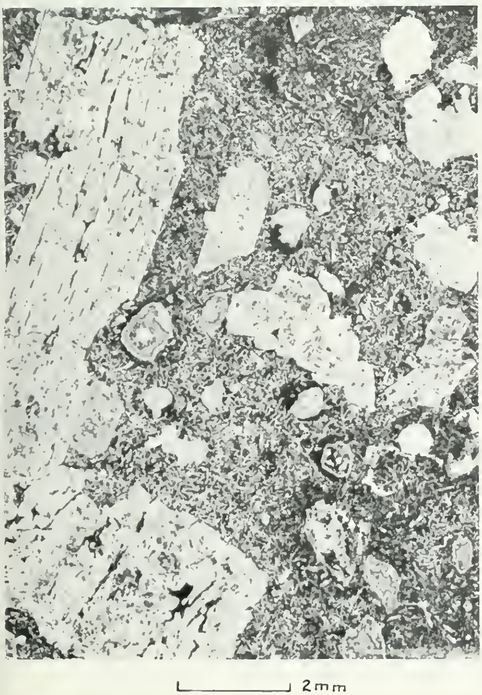
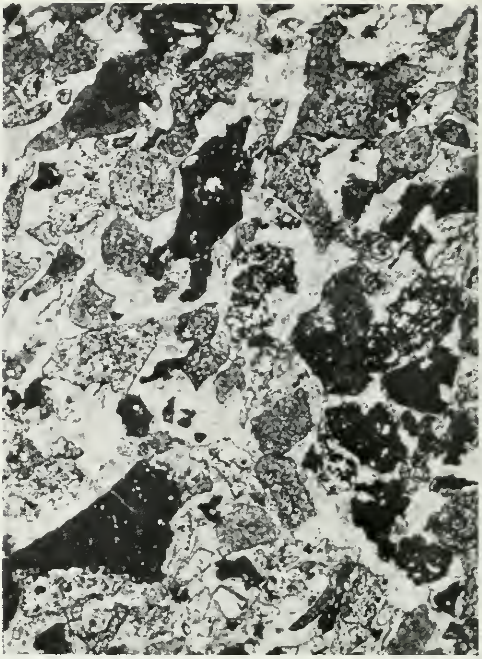


Photo 23 (left). Porphyritic greenstone. Phenocrysts are labradorite, and groundmass consists of laths of andesine and augite in a matrix of glass altered to chlorite. Amygdules contain peripheral chlorite, pumpellyite, and calcite. Skaggs quadrangle (59-454).

Photo 24 (right). Altered tachylitic tuff. Initially composed of fragments of basaltic glass, some of which contained microlites of feldspar and augite (?), in a cement of calcite, but now all glass is altered to chlorite. Dominant feature is preservation of jagged edges and sharp points of fragments. This is interpreted to indicate the fragments were formed during a submarine eruption, and have neither been above water nor subjected to submarine erosion or transport. Probably all of the fragments result from a single eruption, and their color differences result from differences in degree of primary crystallinity and vesicularity. Los Gatos quadrangle (NA 376).



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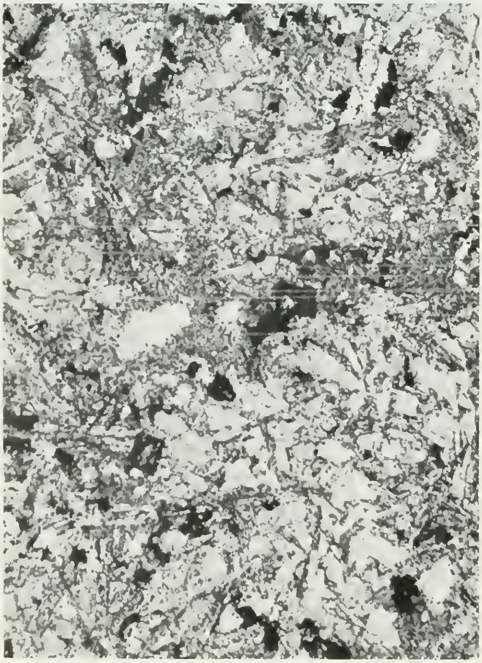

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Photo 25 (left). Diabasic greenstone with large anhedral crystals of fresh augite enclosing euhedral tablets of plagioclase that now consist of albite, pumpellyite, chlorite, and some calcite. A few of the dark areas are magnetite, but most are leucoxene replacements of ilmenite. Gray patches were once tachylite groundmass but are now chlorite. Los Gatos quadrangle (NA 123).

Table 4. Analyses of Franciscan greenstones, with analyses of spilite and tholeiitic basalt for comparison, and molecular norms.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
SiO_2	49.08	52.89	47.8	45.3	51.28	48.19	46.3	46.60	48.8	49.3	46.98	44.90	46.52	45.6	43.8	49.1	51.22	50.08	50.83
TiO_2	1.72	1.12	3.3	2.6	1.33	1.94	1.7	2.87	2.3	1.6	--	1.84	0.92	1.6	1.5	2.0	3.32	2.60	2.03
Al_2O_3	14.68	13.20	12.5	13.5	15.05	13.85	14.4	15.28	21.0	17.3	17.07	9.94	13.76	14.0	11.4	13.8	13.66	13.73	14.07
Fe_2O_3	1.95	4.93	4.8	6.4	2.42	2.82	1.9	3.98	1.6	2.6	1.85	3.10	2.23	1.2	4.1	3.9	2.84	1.32	2.88
FeO	9.63	3.22	11.7	6.1	8.01	7.82	7.3	8.17	5.25	5.5	7.02	8.82	6.84	9.4	7.3	7.7	9.20	9.79	9.05
MnO	0.15	0.12	0.26	0.24	0.25	0.17	0.18	0.08	0.12	0.14	--	0.15	0.07	0.16	0.16	0.2	0.25	0.17	0.18
MgO	6.69	5.67	4.8	6.1	6.07	7.28	9.3	5.4	3.4	3.7	8.29	14.25	9.30	10.15	14.2	6.1	4.55	7.89	6.34
CaO	10.09	10.95	8.3	8.6	7.08	11.28	10.8	10.68	6.5	10.8	12.15	9.38	12.16	6.5	7.5	9.4	6.89	11.50	10.42
Na_2O	4.60	2.56	3.0	2.7	4.43	2.67	2.5	2.26	4.3	3.8	2.54	1.17	1.91	2.2	1.6	3.3	4.93	2.18	2.23
K_2O	0.20	0.13	0.30	1.6	0.12	0.32	0.76	0.85	1.95	0.25	0.53	0.27	0.23	0.21	0.07	0.4	0.75	0.56	0.82
H_2O+	1.18	2.09	2.3	2.7	2.97	3.26	3.6	3.63	3.7	3.8	4.86	4.95	5.15	6.0	6.1	2.4	1.88	0.02	0.91
H_2O-	0.28	0.25	0.36	1.0	0.39	0.15	0.58	0.24	0.65	0.22		0.86	0.39	0.74	1.7	0.4		0.00	--
CO_2	--	2.45	--	2.5	--	0.24	--	0.06	--	--	--	0.02	0.21	1.4	--	0.8	0.94	0.01	--
P_2O_5	0.23	0.18	0.35	0.27	0.13	0.20	0.19	0.36	0.34	0.22	0.09	0.17	0.10	0.15	0.15	0.2	0.29	0.26	0.23
Total	100.48	99.76	99.8	99.6	99.53	100.19	99.5	100.46	99.9	99.2	101.38	99.82	99.79	99.3	99.6	99.7	100.72	100.11	99.99
MOLECULAR NORMS-CATANORMS																			
Q	--	15.1	3.6	3.8	--	--	--	1.7	--	2.1	--	--	--	1.4	--	2.4	--	0.2	3.8
or	1.0	0.5	2.0	10.0	0.5	1.5	4.5	5.5	11.5	1.5	3.0	1.5	1.0	1.0	0.5	2.5	5.0	3.5	5.0
ab	32.0	24.0	29.0	25.5	41.5	25.0	23.5	21.7	40.0	36.5	20.0	11.0	18.0	21.0	15.5	30.5	45.0	19.5	20.5
an	19.2	24.8	21.0	21.2	21.7	26.2	27.0	30.5	30.5	31.2	34.2	22.5	30.0	24.0	25.8	22.7	13.0	26.5	26.7
ne	5.7	--	--	--	--	--	--	--	--	--	2.1	--	--	--	--	--	--	--	--
C	--	--	--	--	--	--	--	--	1.1	--	--	--	--	2.4	--	--	--	--	--
di	23.6	10.8	16.4	4.0	11.2	23.6	22.0	18.4	--	20.0	21.6	20.4	25.6	--	10.4	16.0	11.6	24.0	20.0
hy	--	11.2	17.2	17.4	18.4	16.2	0.6	12.8	3.6	2.8	--	29.4	14.8	42.4	30.6	16.2	14.6	20.8	17.6
ol	13.7	--	--	--	2.1	0.6	17.4	--	7.5	--	16.7	8.4	6.0	--	10.2	--	0.3	--	--
mt	1.9	5.2	5.2	7.0	2.5	3.0	2.1	4.4	1.6	3.0	2.1	3.5	2.5	1.3	4.5	4.2	3.0	1.3	3.1
il	2.4	1.6	4.8	3.8	1.8	2.8	2.4	4.2	3.4	2.4	--	2.8	1.2	2.4	2.2	3.0	4.6	3.8	2.8
ap	0.5	0.5	0.8	0.5	0.3	0.5	0.5	0.8	0.8	0.5	0.3	0.3	0.4	0.3	0.3	0.5	0.5	0.5	0.5
cc	--	6.4	--	6.8	--	0.6	--	--	--	--	--	0.2	0.4	3.8	--	2.0	2.4	--	--
%An in plag	37	51	42	45	34	51	54	58	43	46	63	67	62	53	62	43	22	58	57

1. "Pseudo-diabase," near Mount St. Helena, Calif. (Becker, 1888, p. 98). Analysis by W. H. Melville.
2. Variolitic diabase from margin of "sill," Angel Island, Marin County, Calif. (Bloxam, 1960, p. 564). Analysis by T. W. Bloxam.
3. Fresh diabase (60-804), south side of Sausalito lateral, 500 ft east of U. S. Highway 101, Marin County, Calif. Rapid rock analysis by method described in U. S. Geol. Survey Bull. 1036-C. Analysis by P. L. D. Elmore, S. D. Botts, I. H. Barlow, and Gillison Chloe.
4. Fine-grained diabase (SFS-275), Candlestick sewage tunnel, 1,400 ft north of south portal, San Francisco South quadrangle, San Francisco, Calif. Rapid rock analysis by method described in U. S. Geol. Survey Bull. 1036-C. Analysis by P. L. D. Elmore, S. D. Botts, I. H. Barlow, and Gillison Chloe.
5. "Pseudo-diabase" from Sulphur Banks, Lake County, Calif. (Becker, 1888, p. 99). Analysis by W. H. Melville. Oxides of original given to 0.001 percent, with total of 99.623.
6. Diabasic greenstone (NA224), from crest of ridge 3.45 miles S. 70° E. of apex of Mine Hill, New Almaden district, Santa Clara County, Calif. Analysis by Mrs. A. C. Vlisidis.
7. Diabase (60-809), east edge of Black Mountain greenstone where cut by highway from Point Reyes Station to Petaluma, Marin County, Calif. Rapid rock analysis by method described in U. S. Geol. Survey Bull. 1036-C. Analysis by P. L. D. Elmore, S. D. Botts, I. H. Barlow, and Gillison Chloe.
8. Basalt, near the mouth of Duvoul Creek, 2 miles north of Camp Meeker, Sebastopol quadrangle, Sonoma County, Calif. (Switzer, 1945, p. 7). Analysis by F. A. Gonyer. SO_3 of 0.08 omitted; MgO reported as 5.4 probably in error as other constituents are given to 0.01 and total is incorrect.
9. Pillow lava (SF-2100), 600 ft northeast of Point Bonita lighthouse, Marin County, Calif. Rapid rock analysis by method described in U. S. Geol. Survey Bull. 1036 C. Analysis by P. L. D. Elmore, S. D. Botts, I. H. Barlow, and Gillison Chloe.
10. Greenstone (SF-97), east side of Parker Ave., 300 ft south of Anza Street, Lone Mountain, San Francisco, Calif. Rapid rock analysis by method described in U. S. Geol. Survey Bull. 1036 C. Analysis by P. L. D. Elmore, S. D. Botts, I. H. Barlow, and Gillison Chloe.
11. "Fourchite" (metagreenstone) from Angel Island, Marin County, Calif. (Ransome, 1894, p. 231). Analysis by F. L. Ransome.
12. Altered tachylitic tuff (NA-325), from point of 1,100 ft altitude, 3.44 miles S. 55½° E. of apex of Mine Hill, New Almaden district, Santa Clara County, Calif. Analysis by Mrs. A. C. Vlisidis.
13. Altered diabase from main "sill," Angel Island, Marin County, Calif. (Bloxam, 1960, p. 564). Analysis by T. W. Bloxam.
14. Tuffaceous greenstone (SFS-192), north side of road from Sharp Park to Skyline Blvd., 3,050 ft east of BM13, San Francisco South quadrangle, San Mateo County, Calif. Rapid rock analysis by method described in U. S. Geol. Survey Bull. 1036-C. Analysis by P. L. D. Elmore, S. D. Botts, I. H. Barlow, and Gillison Chloe.
15. Tuffaceous greenstone (SFS-131), 8,600 ft southeast of Mussel Rock, San Francisco South quadrangle, San Mateo County, Calif. Rapid rock analysis by method described in U. S. Geol. Survey Bull. 1036-C. Analysis by P. L. D. Elmore, S. D. Botts, I. H. Barlow, and Gillison Chloe.
16. Average of 1 6.
17. Average spilite (Sundius, 1930, p. 9).
18. Tholeiitic basalt, Kilauea, Island of Hawaii (Eaton and Murata, 1960, p. 936). Analysis by L. N. Tarrant.
19. Average of 137 normal tholeiitic basalts and dolerites (Nockolds, 1954, table 7, vii, p. 1021).

are holocrystalline with intergranular, and less commonly diabasic, texture. The more abundant finer grained varieties, however, contain considerable altered mafic glass and exhibit a wider range of textures, which commonly vary within a few inches or in a single outcrop. The extreme variation is shown by the pillows in which the texture may range from diabasic or subophitic in the core, through different kinds of variolitic textures due to subradial or plumose development of feldspar or augite, to chloritic aggregates replacing a peripheral shell that once was mafic glass. Some varieties of the volcanic rocks are porphyritic, locally with phenocrysts up to an inch in size; some are vesicular or amygdaloidal.

Plagioclase of the greenstones ranges in composition from bytownite or laboradorite to albite, though perhaps much of the more sodic plagioclase is secondary. It forms large more or less equant phenocrysts, irregular laths in rocks with intergranular texture, or unusually long and thin laths with random or radial orientation in a glassy groundmass. Typically the feldspar of the groundmass shows no preferred orien-

Figure 11. Location of analyzed greenstones listed in table 4.

tation that might be attributed to flow during or after its growth.

The pyroxenes are variable in composition and occurrence. Normal augite seems to be the most common variety, but subcalcic augite and even pigeonite are fairly common, and titanaugite is frequently reported to occur in the coarser grained greenstones. Fine-grained pyroxenes with plumose, radial, or needlelike habit occur in pillows where they appear to have grown in glass rather than in a melt.

Olivine generally is absent, but areas of a serpentine mineral with relict outlines of olivine phenocrysts and microlites have been recognized as a constituent of the greenstones in a few places (see photo 18).

Pumpellyite may take the place of pyroxene in the pillow lavas, and in some it occurs in abundance with albite in fine-grained aggregates that replace more calcic plagioclase. Pumpellyite also is well developed in veins and as fillings in vesicles in some of the pillow lavas.

Magnetite is generally present, and ilmenite, leucoxene, and sphene are often noted.

Altered mafic glass is a major constituent of many of the lavas and also is the most prominent substance in the breccias, agglomerates, and tuffs. In some cases it has recrystallized to a green chlorite or nontronite, but, particularly in the tuffs, much of it has a deep, rich brown color and is recrystallized only to the extent that one can tell that it consists of minute crystals rather than glass. X-ray studies of a few examples of this material gave pumpellyite patterns. That such material was originally glass is shown by its fluidic texture in photos 20 and 21.

Chemical features. Chemical analyses of 15 Franciscan greenstones are given in table 4 together with molecular norms, and the distribution of sample localities is shown in figure 11. Also included in the table for comparison are analyses and molecular norms of average spilite, a typical tholeiitic basalt, and an average of 137 tholeiitic basalts and dolerites. The Franciscan greenstones differ from the tholeiitic basalts most markedly in their abnormally high content of combined water, and for this reason they have been arranged in the table from left to right in order of increasing amounts of water. With this arrangement it becomes apparent that the rocks with the most water are those which differ the most from tholeiitic basalt, and as the water content goes up the magnesia content increases, and silica, lime, and soda decrease. It should also be noted that this arrangement groups the massive diabases to the left and the tuffaceous rocks with a high content of altered mafic glass on the right. This grouping suggests that the massive rocks more nearly correspond chemically to the initial magma, and that the others have undergone more alteration, as one might expect from their fragmental character.

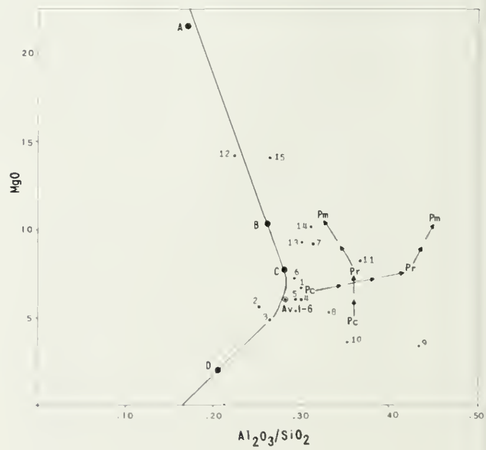


Figure 12. Plot of MgO against Al_2O_3/SiO_2 weight ratio. Tholeiitic basalt series (A-D), Franciscan greenstones numbered as in table 4, and parts of Franciscan pillow lavas given in table 5.

Whether some or all of the massive rocks closely approximate the original magma, however, is still an unsolved problem.

One approach to the solution of this problem can be made by comparing the analyses to those of typical rocks of the tholeiitic basalt series. Figure 12 indicates the differentiation trend as determined by Murata (1960), with A, B, C, and D representing averages for picrite, tholeiitic olivine basalt, tholeiitic basalt, and granophyre, and the line through these points indicating the normal products of differentiation of tholeiitic olivine basalt magma. Plots of the Franciscan greenstone analyses, 1-15, are shown on this diagram. Analyses 1-6 fall near the trend line and close to the average tholeiitic basalt, whereas the others are scattered and depart rather widely from it. From a study of this diagram it seems a reasonable assumption that the diabase analyses, 1-6, come close to representing the original magma, and their average composition is shown in table 4, column 16. A comparison of this average with the average tholeiitic basalt and spilite, columns 19 and 17, indicates the average Franciscan magma is much like a normal tholeiitic magma, but it has a soda content intermediate between spilite and tholeiite.

Origin. Analysis of the more hydrous Franciscan greenstones show changes from the supposed initial magma other than the simple addition of water. How and when these changes were brought about cannot yet be proven, but we suspect significant changes were brought about by an initial reaction of the molten magma with sea water. Because the pillow lavas and their matrices seem to provide samples of the same magma that have had different opportunities for reaction, depending on whether they are from the core, rim, or matrix, samples of these materials from the same pillow have been obtained and analyzed. However, before discussing these analyses, we will describe the pillows and suggest the origin that seems responsible for their unusual form.

The term "pillow lava" has been used variously for rounded bulbous forms on the surface of lava that flowed into water (Anderson, 1910), for rounded masses that form along the base of lava that flowed over water-saturated muds or tuffs (Fuller, 1931), and for piles of separate more or less rounded blobs of lava closely packed one above the other or separated by a tuffaceous matrix (Wilson, 1960). So far as we know, all the Franciscan pillow lavas are in the latter category, and to us it seems useful to restrict the term "pillow lava" to masses that are composed of discrete pillows which are not connected either to the top or base of a massive flow or even to each other. The Franciscan pillows, where they can be seen clearly, or dug out, show no connection from one to the other, such as "budding," nor are the piles of pillows transected by a network of feeders. Each pillow is an entity in itself. It consists of a more coarsely crystalline core, a finer grained marginal zone from one to several inches thick, and a thin shell of altered glass. Matrix material, which also is generally altered glass, may be virtually nil or may amount to as much as half of the volcanic pile. Piles of larger pillows generally have the least matrix. Locally limestone or chert, or both, separate the pillows; and rarely one finds pillowlike masses completely isolated in shale. The size of the pillows is generally between 1 and 3 feet, although it ranges from about an inch to at least 10 feet. In any single locality the pillows tend to be more or less the same size. Large pillows tend to be more irregular, and small ones are more nearly spherical. Although some contain no vesicles, many pillows contain an abundance of calcite or chlorite-filled vesicles which are only a millimeter or two in size. Phenocrysts are not generally found, but when present may show a concentration in the central part of the pillow or in a peripheral zone. The glassy selvage and matrix locally contain broken phenocrysts.

The origin of pillows has been discussed by many authors and variously ascribed to budding (Lewis, 1914), to the action of a secondary jet of lava being extruded from a spiricle as a result of the lava overriding and incorporating water, to billowing due to the buildup of gas pressure in a part of a flow (Stark, 1938), or to mixing of lava and sea water (Zavaritsky, 1960). Inasmuch as there are in the Franciscan eugeosynclinal assemblage piles of pillows hundreds of feet thick without associated massive flows, and without evident connections between pillows, only the proposal of Zavaritsky seems adequate to explain their origin. However, Zavaritsky does not describe how he believes the lava and sea water become mixed. A mechanism that might account for these piles of separate pillows is a violent jet eruption of highly fluid lava on the sea floor. The breaking up of this jet stream of lava into large drops or blobs, which are chilled as they fall back about the vent, then builds up a pile of pillows. As a drop of magma, forming a pillow, falls through the water its surface solidifies but remains thin enough to yield under the weight of the drop to conform to the shapes of the earlier pillows onto which it settles to rest. As the upper surface of the pillow generally is not appreciably deformed, the rate of accumulation must be slow enough to permit the solidified border to thicken between the time the pillow came to rest and the time the next pillow settled on it. Matrix material would consist either of the finer pieces of magma that were pulled off during the formation of the drop or of fragments resulting from explosive activity.

If this eruptive mechanism, proposed to explain the features we observed, is the true origin of the pillows, the eruption must have taken place beneath a cover of water deep enough to contain the lava jet, which, by comparison with subaerial fountain eruptions, must be several hundred feet or more. Also, if this explanation holds, the pillows, and particularly the accompanying matrix, have had ample opportunity to react with the

Table 5. Analyses of core, rim, and matrix of Franciscan pillow lavas, with similar analyses from other pillow lavas for comparison.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	Core	Rim	Matrix	Feeder?	Core	Rim	Matrix	Core	Rim	Core	Rim	Core	Rim	Matrix	Core	Rim	Matrix	Core	Rim	Matrix
SiO_2	42.6	44.9	45.3	46.3	46.0	39.8	36.4	47.0	45.2	51.4	47.4	48.38	50.40	30.24	47.16	56.62	35.33	45.22	51.14	29.46
TiO_2	0.76	0.95	0.62	1.7	2.3	2.4	1.8	1.1	1.2	1.8	1.8	1.21	1.55	0.58	2.02	1.89	3.44	1.96	2.15	3.01
Al_2O_3	15.2	15.9	14.4	14.4	14.2	16.7	16.3	14 1	16.2	14.9	14.9	12.73	14.16	16.83	15.84	16.01	15.21	14.38	15.88	16.95
Fe_2O_3	5.7	3.9	4.0	1.9	2.1	1.7	3.2	1.5	1.6	2.1	2.1	3.17	1.63	3.95	5.66	3.17	3.89	6.75	2.39	5.23
FeO	4.4	6.6	6.6	7.3	7.9	7.6	11.9	5.8	8.0	7.4	10.4	6.52	8.54	18.72	5.68	2.32	11.06	5.00	5.15	15.53
MnO	0.18	0.22	0.20	0.18	0.18	0.17	0.18	0.21	0.19	0.20	0.23	0.17	0.16	0.28	0.14	0.07	0.32	..	0.09	0.10
MgO	4.8	7.9	10.9	9 3	6.5	7.8	10.5	4 5	7.7	5.1	6.6	7.96	8.58	16.73	6.36	3.17	13.46	6 58	6.02	16.08
CaO	15.8	8.5	5.2	10 8	9 4	8.2	5 1	13.2	9.0	9.6	7.9	9.48	5.90	1.92	5.52	4.64	4.03	11.13	9.16	2.97
Na_2O	3.1	2.7	0.14	2.5	4.1	1.5	2.2	4 6	2.8	4.1	3.9	3.92	4.28	0.27	5.61	8.41	0.59	4.43	4.50	0.84
K_2O	0.02	0.76	2.0	0.76	0.58	3.4	1.0	0.24	1.6	0.06	0.30	0.08	0.16	0.02	0.44	0.58	2.19	0.63	0.62	0.51
H_2O+	3.8	5.0	7.4	3.6	3.7	5.8	8.0	2.9	4.7	3.6	4.2	6.14	4 49	10.18	3.47	2.08	8.72	1.92	3.01	9.64
H_2O-	0.40	1.2	1.7	0.58	0.72	1.0	1.3					0.16	0.13	0.27	0.11	0.06	0.24	0.25	0.12	0.11
CO_2	2.7	1.2	1.2	..	1.6	3.4	1.4	5.5	1.8	0.7	0.22	..	..	0.08	2.07	1.59	1.10	1.78	..	..
P_2O_5	0.08	0.08	0.04	0.19	0.36	0.43	0.24	0.13	0.15	0.17	0.19	0.15		0.11	0.30	tr	0.19	..	0.26	tr
Total	99.5	99.8	99.7	99.5	99.6	99.9	99.5	100.8	100.1	101.1	100.1	100.07	99.98	100.18	100.38	100.61	99.77	100.03	100.49	100.43
Sp. G. (Powder)	3.02	2.86	2.76	2.97	2.87	2.77	2.76													

1-11. Rapid rock analyses by method described in U. S. Geol. Survey Bull. 1036-C. Analyses by P. L. D. Elmore, S. D. Botts, I. H. Barlow, and Gillison Chloe.
1-3. Franciscan pillow lava; from west side of U.S. Highway 101, at a point 400 ft north of north portal of twin Waldo Tunnels. San Francisco North quadrangle, Marin County, Calif.
4-7. Franciscan pillow lava, and diabase that may represent a feeder; from east edge of Black Mountain greenstone mass where cut by highway from Point Reyes Station to Petaluma, Marin County, Calif.
8-11. Pillow lava; from west side of State Highway 20, about 400 ft south of south side of Yuba River. Smartsville quadrangle. Yuba County. Calif. Collected by L. D. Clark.
12-14. Zoned pillow and matrix, Anglesey, Great Britain (Vuagnat, 1949, p. 235). Analysis by J. Jacob.
15-17. Spilite pillow and matrix, Hornli, Arosa, Switzerland (Vuagnat, 1946, p. 189). Analysis by M. Vuagnat.
18-20. Diabase of the Champatsch Alps (Vuagnat, 1946, p. 190). Analysis 18 by L. Hezner; 19-20 by M. Vuagnat. All samples from same outcrop but apparently not from same pillow.

heated sea water with which they were in contact, as was suggested by the chemical analyses presented in table 4.

Additional analyses of the core, rim, and matrix of two Franciscan pillows are given in table 5, which also includes comparable sets of analyses from the Sierra Nevada, Great Britain, and the Alps. It is quite apparent from these analyses that within a single pillow, or from a pillow to its matrix, there are major differences in chemical composition, thus suggesting that single analyses of pillow lavas can be quite misleading.

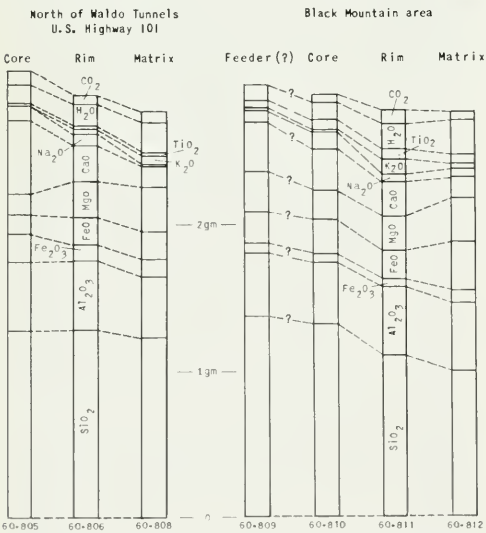


Figure 13. Bar graph of two sets of Franciscan pillow lava analyses (1-3 and 4-7 of table 5) in terms of weight of oxides per unit volume, or grams per cubic centimeter, assuming no change in volume or porosity.

For the Franciscan pillow lavas, powder specific gravity data are available, and this permits us to calculate the quantity of oxides in a unit volume of rock and thus arrive at possible gains and losses, if we assume no change in volume or porosity. Figure 13 shows graphically the changes in quantities of oxides found in the core, rim, and matrix for two sets of Franciscan samples (1-3 and 4-7 of table 5), and the same data are shown in numerical form in table 6. For the second set of analyses we have also included in figure 13 the data for a massive diabase from the same area, as it may represent a feeder, but the relation of this rock to the pillows could not be definitely established in the field.

Figure 13 and table 6 show the same general trends in chemical differences between the core, rim, and matrix in both sets of analyses, but the amounts of change in the various oxides are not consistent. Silica becomes progressively less abundant from center to matrix, but is markedly less in only one of the two sets. Alumina and titania show no significant change. Lime decreases as magnesia increases from core to matrix in each case, and these changes are very large in percent. Ferrous iron increases from core to matrix, and total iron shows a small increase. The changes in alkalies are interesting because they are very large per-

Table 6. Analysis of sets of samples from two Franciscan pillow lavas presented in terms of weight of oxides per unit volume (Sp. G. x percent in rock), assuming no change in volume or porosity.

	North of Waldo Tunnels U. S. Highway 101				Black Mountain area				
	Core 60–805	Rim 60–806	Matrix 60–808	Change 805–808	Feeder(?) 60–809	Core 60–810	Rim 60–811	Matrix 60–812	Change 810–812
SiO_2	128.6	128.4	125.0	−3.6	137.5	132.0	100.2	100.5	−31.5
TiO_2	2.3	2.7	1.7	−0.6	5.0	6.6	6.6	5.0	−1.6
Al_2O_3	45.9	45.4	39.7	−6.2	42.8	40.8	46.3	45.0	+4.2
Fe_2O_3	17.2	11.2	11.0	−6.2	5.6	6.0	4.7	8.8	+2.8
FeO	13.3	18.9	18.2	+4.9	21.7	22.7	21.0	32.8	+10.1
MgO	14.5	22.6	30.1	+15.6	27.6	18.7	21.6	29.0	+10.3
CaO	47.7	24.3	14.4	−33.3	32.8	27.0	22.7	14.1	−12.9
Na_2O	9.4	7.7	0.4	−9.0	7.4	11.8	4.2	6.1	−5.7
K_2O	-	2.2	5.5	+5.5	1.2	1.7	9.4	2.8	+1.1
H_2O	11.5	14.3	20.4	+8.9	10.7	10.6	16.1	22.8	+12.2
CO_2	8.1	6.8	3.3	−4.8	--	4.6	9.4	3.9	−0.7
P_2O_5	0.3	0.3	0.1	−0.2	0.6	1.0	1.2	0.7	−0.3

centagewise, but they do not show a linear trend from core to matrix. Soda decreases from core to rim in both cases, but in one case shows a slight increase from rim to matrix. The decrease in soda from core to rim was also found in other Franciscan pillows by Hopgood (1962) and Gluskoter (1962). Potash is minor in the core but becomes concentrated in either the rim or matrix. The soda/potash ratio decreases from core to matrix, but in one case is much smaller in the rim than in the matrix. Orville (1960) has shown experimentally the effectiveness of a reciprocal alkali transfer between two parts of a rock mass at different temperatures, with K moving to the low temperature and Na to the high temperature part. As the temperature gradient in a pillow beneath its glassy selvage must initially be very large, this may account for the large concentration of sodium in the hotter interior and potassium in the cooler marginal zone.

Gains and losses calculated by using the powder specific gravity, such as those shown in table 6, are based on the assumptions that a unit volume of the original material is altered to a similar unit volume of the product by a replacement process, with migration of constituents into or from the material as required by the analysis and that the porosity remains constant. In the absence of evidence for volume-for-volume replacement, one may also calculate possible gains and losses by assuming that the quantity of some oxide remains constant. If we assume that the magma that reacted to form the glassy matrix did not absorb the large quantities of magnesium indicated by the gain from core to matrix in table 6, we may recast the analyses holding the quantity of magnesium constant. Table 7 shows the results of such a calculation, which probably more closely portrays the changes that have actually taken place, though the improbable loss of H_2O in the first set of analyses of table 8 indicates this treatment of the data is not exact. However, we believe the large losses of silica, alumina, lime, and soda, and smaller losses of iron are significant; the only increase that might be attributed to reaction with the sea water is in potash.

It is perhaps at first surprising to see that the rims of the pillows differ so much from the matrix materials. Their different geologic history, however, suggests that this difference is expectable. The matrix material represents fine droplets or fragments of glass that were quickly chilled, with a maximum of surface area available for reaction with the sea water both during the chilling and subsequent to it. The rims of the pillows inside the thin glassy selvage have had a different history. Because of the sealing effect of the selvage, the opportunity for reaction with the sea water has been greatly reduced; but within the pillow, when it first settles to the sea floor, part of the material is still molten, while part is glassy, and large temperature differences between the hot core and cool rim favor the migration of some of the elements. In addition, after the pillow reached the sea floor and

Table 7. Analyses of sets of samples from two Franciscan pillow lavas calculated in terms of weight of oxides per unit volume, as in table 6, but with volume of matrix reduced to contain the same amount of magnesia as in unit volume of core.

	North of Waldo Tunnels U. S. Highway 101			Black Mountain area		
	Core 60–805	Matrix 60–808	Change 805–808	Core 60–810	Matrix 60–812	Change 810–812
SiO_2	128.6	60.4	−68.2	132.0	64.8	−67.2
TiO_2	2.3	0.8	−1.5	6.6	3.2	−3.4
Al_2O_3	45.9	19.2	−26.7	40.8	29.0	−11.8
Fe_2O_3	17.2	5.3	−11.9	6.0	5.6	−0.4
FeO	13.3	8.8	−4.5	22.7	21.2	−1.5
MgO	14.5	14.5	0	18.7	18.7	0
CaO	47.7	6.7	−41.0	27.0	9.1	−17.9
Na_2O	9.4	0.2	−9.2	11.8	3.9	−7.9
K_2O	--	2.7	+2.7	1.7	1.8	+0.1
H_2O	11.5	9.8	−1.7	10.6	14.7	+4.1
CO_2	8.1	1.6	−6.5	4.6	2.5	−2.1
P_2O_5	0.3	0.1	−0.2	1.0	0.5	−0.5

was covered by other pillows or matrix, the temperature change in the marginal part was probably reversed, as the heat from the still-molten core would be dissipated outward through the pillow until an even heat distribution throughout the volcanic pile was attained. This process of gradual reheating of the outer part of the pillow is somewhat similar to annealing, and it seems likely that the unusual variolitic and plumose growths of feldspar and augite were developed in a glassy or microcrystalline ground-mass at this stage, rather than during the initial cooling. The similar development of pumpellyite in varioles, as shown in photos 18 and 19, suggests it may also crystallize during this period of reheating. As has been mentioned, the peculiar distribution of the alkalies also may result from uneven heat distribution during this period.

The sets of analyses of non-Franciscan pillows shown in table 5 indicate large chemical differences, but the changes in the amounts of constituent oxides here, as in the Franciscan rocks, are not the same in all cases. The differences in composition between the cores of the pillows and the accompanying matrices, however, are similar to the differences shown in the Franciscan rocks, except for the iron; the matrices contain less silica, lime, and soda, and more magnesia. If calculated on a constant magnesia basis, the matrices also contain much less alumina, but the iron is nearly constant. The differences between cores and rims of pillows represented by these analyses do not all show the same trends, doubtless indicating either differences in initial reactions or changes during cooling that are not now understood.

To sum up, the parts of the Franciscan pillows and their matrices show gross differences in chemical composition. There is no reason to believe that any of these three component parts closely approximates the initial composition of the magma, though, by comparison with the diabasic rocks, we can see that the cores of the pillows are most like the magma. The matrix and, to some extent, the margins of the pillows seem to have reacted with sea water. The chief differences between the central parts of the pillows and the matrices are an apparent loss of silica, lime, and soda and an apparent gain of magnesia and perhaps some potash. If the matrix material has not picked up large amounts of magnesia from the sea water, losses of silica and lime are still greater than suggested by the analyses, and there is a large loss of alumina, as well. Secondary changes in composition within the pillows are perhaps due to the migration of soda and potash in response to the existing steep thermal gradients.

Having seen the significant changes in composition associated with the pillow lavas, let us now return to an examination of the chemical analyses shown on table 4. We indicated that the analyses of the diabasic rocks were similar to normal tholeiitic basalt and its differentiates and suggested that they approximated the original magma, whereas the other more hydrous rocks were anomalous. Some of the more hydrous rocks are pillow basalts and others are tuffs, and, as they show variations consistent with those demonstrated for single pillows and their matrices, it seems likely their composition has also been altered by the magma having reacted with sea water. Because of these chemical changes, individual analyses of Franciscan greenstones or tuffs are likely to be misleading when used to indicate the composition of the initial magma, and even the average of a whole series of analyses cannot be expected to equal the composition of the parent magma.

As the Franciscan pillow lavas have been regarded as spilites by many authors, some discussion of the problem of nomenclature seems desirable, even though we do not yet know how widespread spilites may be in the assemblage of Franciscan rocks. Spilite by one definition is a basaltic type of rock with albite or albite-oligoclase instead of the more calcic plagioclase that is normal for basalt. If this definition is used, many of the Franciscan pillow lavas are spilites, but a few are basalts. Another definition of spilite requires the rock to have more soda than is normal for basalt, and, as is shown by table 4, some of the Franciscan pillow lavas will also qualify as spilites on this basis. Others that contain albite as the only plagioclase have a soda content like that of basalt.

The genesis of spilites, which are a prominent component of many of the eugeosynclinal assemblages of the world, is controversial. The most debated points are whether spilites represent direct crystallization of a soda-rich magma, or of a magma contaminated by sea water, or whether they represent only a kind of metamorphism in which calcic plagioclase has reacted to release calcium to form epidote or other minerals, leaving a sodic residue to form albite. Neither enough analyses nor sufficient detailed petrography are available to reach firm conclusions regarding the origin of the Franciscan greenstones that can be regarded as spilites; however, some of the data presented should be indicative. The analyses of the pillow lavas presented in this report show that the cores of some pillows are rich enough in soda to be regarded as spilites under a chemical definition but the rim and matrix are not, yet both core and rim contain albite. Enrichment in soda of the core of a pillow seems to be attributable to migration of soda during cooling, and impoverishment in soda of the rim and matrix suggests that the magma has lost, rather than gained, soda as a result of its contact with sea water. Analyses of the least hydrous diabasic rocks (analyses 1-6, table 4), believed to be the rocks most like the original magma, include two analyses with a soda content of about 4.5 percent, which is only a little less than that of average spilite; however, both of these are old analyses, so the reported soda may be too high. The analytical data that seems to suggest the original magma of the Franciscan

Table 8. Analyses of keratophyres.

	1	2	3	4
SiO_2	64.8	77.08	68.04	69.6
TiO_2	0.76	0.22	0.46	0.18
Al_2O_3	14.3	12.43	12.09	14.4
Fe_2O_3	1.4	1.48	3.81	2.8
FeO	4.1	0.55	3.21	1.5
MnO	0.12	0.07	0.10	0.15
MgO	1.4	0.23	1.97	0.30
CaO	2.0	0.88	3.41	0.55
Na_2O	4.9	6.13	5.04	5.6
K_2O	2.3	0.15	0.00	3.8
H_2O^+	2.0	0.92	1.89	0.92
H_2O^-	0.32	0.31	0.54	0.46
CO_2	0.80	--	-	0.09
P_2O_5	0.21	0.02	0.05	0.03
Total	99.4	100.47	100.61	100.4

1. Keratophyre from Pfeiffer Big Sur State Park, Point Sur quadrangle, Monterey County, Calif. Powder density, 2.64. Rapid rock analysis by method described in U.S. Geol. Survey Prof. Paper 1036 C. Analysis by Paul Elmore, Samuel Botts, Ivan Barlow, and Gillison Chloe.
2-3. Quartz keratophyre, volcanics near Del Puerto Creek, Maddock (1955), Mount Boardman quadrangle, California. Analysis by R. Klemen.
4. Keratophyre with a few percent of secondary(?) quartz (61-12), from west side of Little Black Mountain, Skaggs quadrangle, Sonoma County, Calif. Powder density, 2.68. Rapid rock analysis by Paul Elmore, Samuel Botts, Gillison Chloe, Lowell Artis, and H. Smith.

greenstones was somewhat spilitic needs to be confirmed by additional analyses of relatively unaltered diabasic intrusive rocks before we can be confident that any of the Franciscan magma represents a spilitic type distinct from normal tholeiitic magma.

Keratophyre. Keratophyre and quartz-keratophyre, rocks chemically similar to spilites but with more silica or free quartz, have been found in several areas mapped as Franciscon. Crittenden (1951, p. 19-20) first reported quartz-keratophyre near the south edge of the San Jose quadrangle, and Robinson (1956) noted similar rocks in the Hayward quadrangle along the western flank of the Mount Hamilton range. On the eastern side of the range, along Del Puerto Creek, there is an extensive thickness of keratophyre that has been studied by Maddock (1955), and, although they are not completely mapped, similar rocks form extensive areas of outcrop along the east edge of the range at least as far south as the Ortigalita Peak quadrangle (Briggs, 1953a). Although the keratophyres have been mapped as part of the Franciscan, they appear to be directly, and perhaps conformably, overlain by fossiliferous Knoxville shales in the Hayward quadrangle on the west side of the Mount Hamilton range and in the Mount Boardman and Pacheco Pass quadrangles on the east side. Elsewhere in the Coast Ranges, keratophyres occur as igneous intrusions into rocks mapped as Franciscan in the Pfeiffer Big Sur State Park in the Point Sur quadrangle (Oakeshott, 1951), and we find similar relations in the south-central part of the Skaggs quadrangle. Keratophyres have also been found by J. R. McNitt (oral communication, 1960) in the Kelseyville quadrangle. The character of these occurrences does not permit a positive decision regarding whether or not the keratophyre is an integral part of the eugeosynclinal assemblage or merely intrusive into it.

The keratophyres can generally be distinguished from the more typical mafic greenstones by their lighter color and, in some areas, by the pink phenocrysts in them. Thin sections reveal the phenocrysts are chiefly albite, and in the quartz keratophyres the quartz occurs as either euhedral crystals or irregular interstitial patches. Original ferromagnesian minerals are generally altered to stilpnomelane or chlorite. Four chemical analyses of keratophyres are given in table 8.

BEDDED CHERT AND ASSOCIATED SHALE

Chert, and the distinctive shale that is generally interbedded with it, probably constitutes less than half a percent of the entire assemblage of Franciscan rocks. It is, however, of greater interest both economically and geologically than its minor abundance would suggest. The chert is widely used as road-base material; it is the host rock for all of the productive manganese deposits in the Franciscan; and it is the principal host rock at some mercury mines (Bailey, 1946). Chert also is a prominent component of stream gravels used for concrete aggregate, but is deleterious for this use if too abundant (Goldman, 1959). Geologically, chert is of special interest, because it provides information on the depth of deposition of some parts of the eugeosynclinal assemblage. In addition, because of its greater resistance to erosion than most of the other rocks of the Franciscan, chert is generally well exposed, and in many places it provides the only outcrops rising above smooth grass-covered slopes.

Occurrence and megascopic features. Bedded cherts are widely distributed throughout the broad areas of Franciscan rocks, but their distribution is not entirely haphazard. They are clearly most abundant in areas where volcanic rocks are common, and they most commonly occur strategraphically directly above greenstone. This stratigraphic relation is so common that it provides a useful guide to the upright or overturned position of a section. The relative abundance of chert in the parts of the Franciscan that are of different ages is not well known. The Franciscan rocks just east of Mount Hamilton, which are regarded by some geologists as among the oldest of Franciscan rocks, contain little greenstone and chert; other Franciscan rocks also presumed to be pre-Knoxville in age contain abundant chert. Mid-Cretaceous rocks of the Franciscan Formation in the San Francisco Bay area include much chert, but farther north the "coastal belt" rocks of Bailey and Irwin (1959), that are in part of similar age, contain little chert.

Although Franciscan cherts show considerable diversity in appearance, all are fine-grained, hard, highly siliceous rocks, and most are highly colored. They owe their color to finely divided iron oxides or hydroxides and are, therefore, generally red, deep reddish brown, buff, or some shade of green. Also, because of

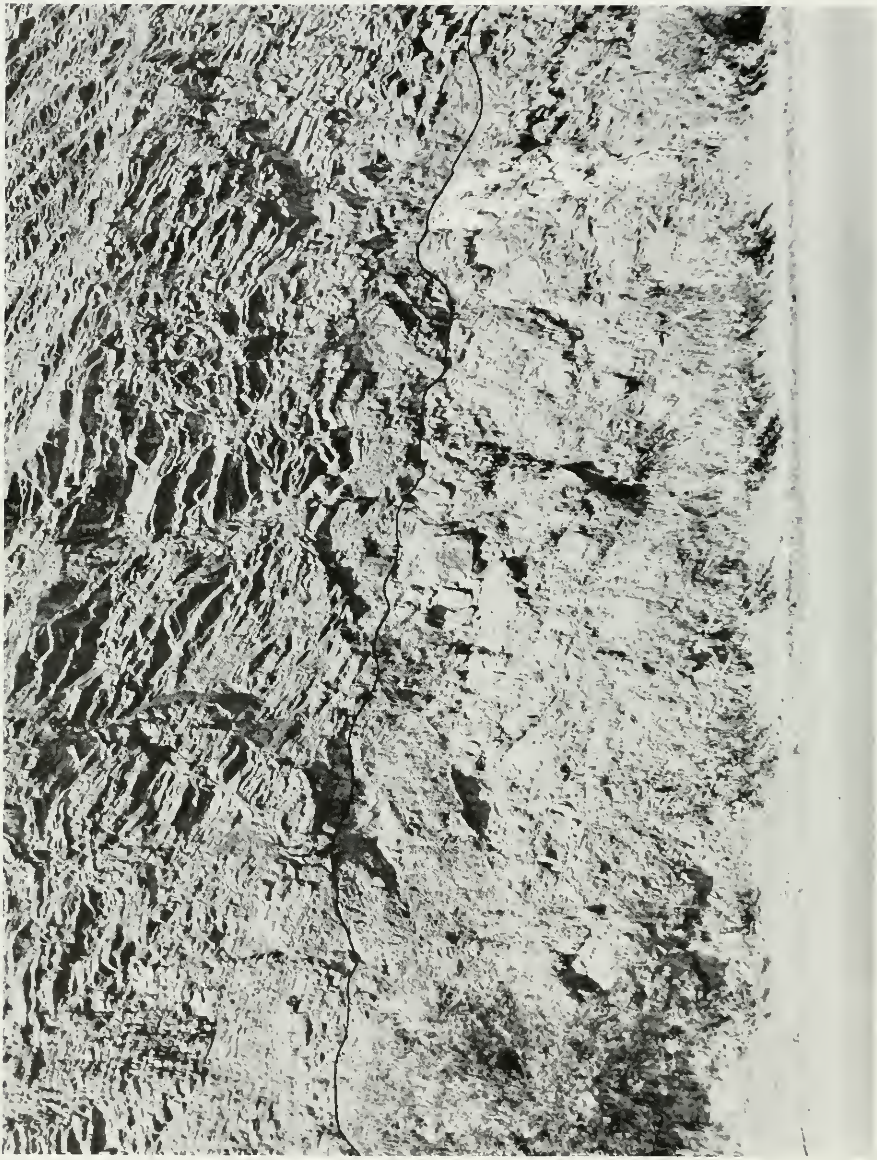


Photo 26. Franciscan red chert overlying pillow lava. Small water seep is on the contact. U. S. Highway 101. North of Golden Gate bridge.

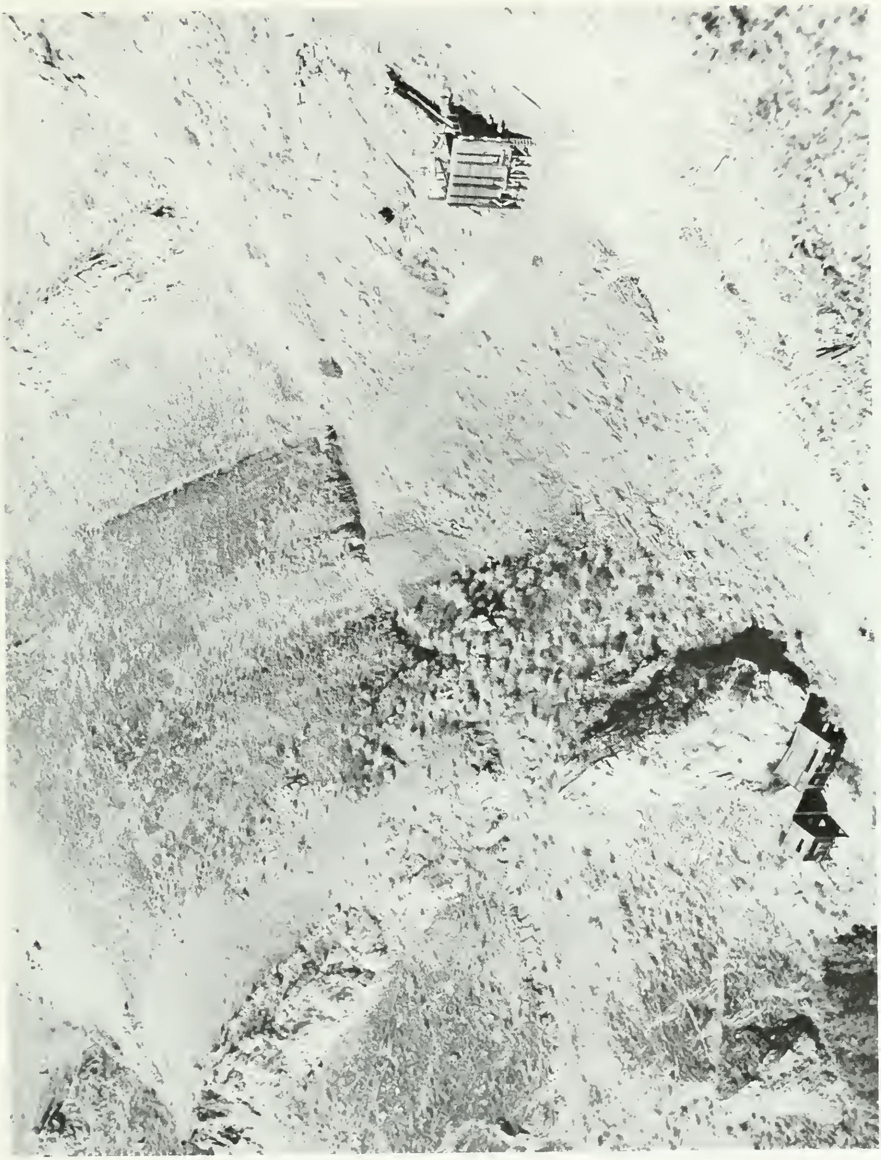


Photo 27. Chert-shale lenses in the Buckeye mine area, Carbona quadrangle. Road past ore bin leads to upper workings of Buckeye manganese mine.

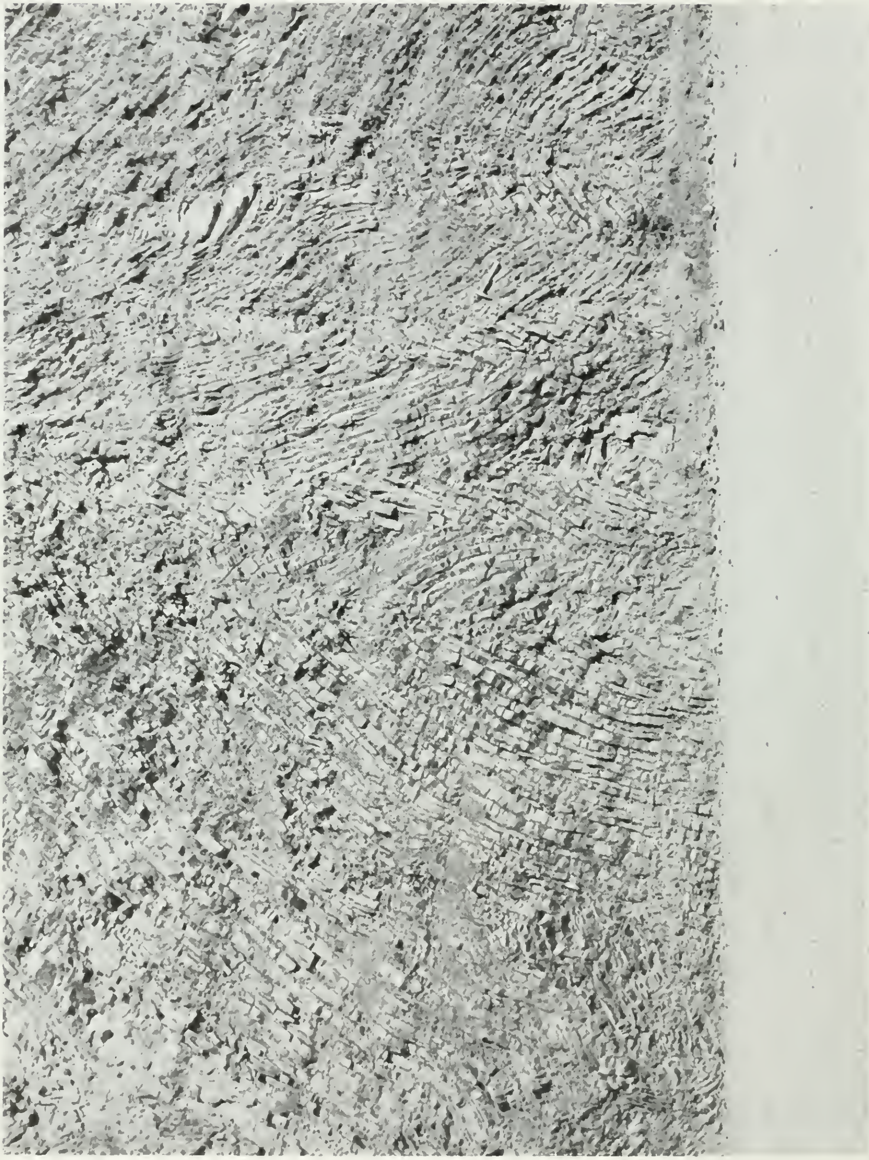


Photo 28. Rhythmically bedded Franciscan red chert showing chevron folds. Road-cut on highway between Dos Rios and Covella in the Laytonville quadrangle.

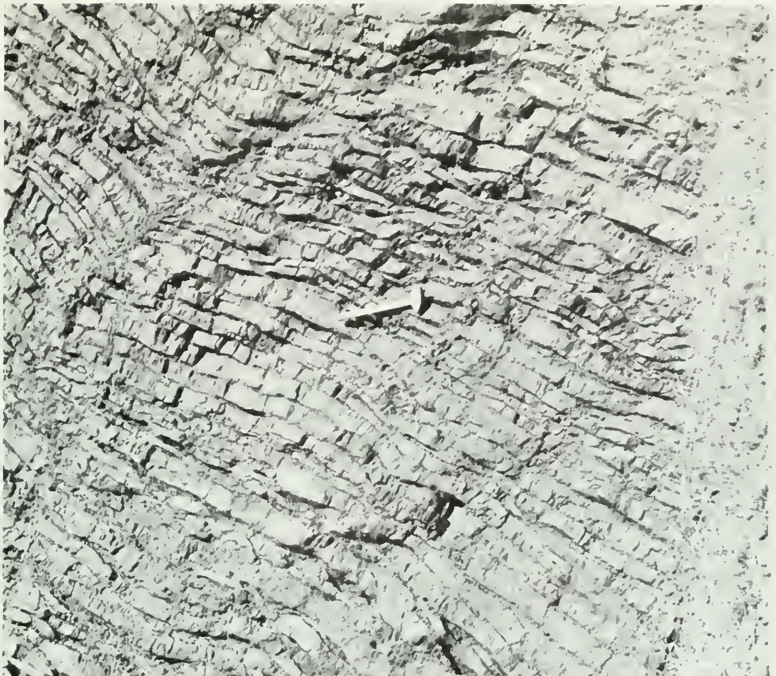


Photo 29. Franciscan red chert north of Golden Gate bridge on north side of road to Sausolito, showing rhythmic alternation of thin-bedded chert and shale beds.

Photo 30. Detail of bedding of Franciscan red chert in Skaggs quadrangle showing pinch and swell structure. Note discontinuous chert lenses to left of knife.

Photo 31. Detail of unusually irregular "bedding" in Franciscan red chert. Skaggs quadrangle.

1mm

Photo 32. Red chert containing unusually abundant tests of radiolaria. The minerals visible are very fine grained quartz, goethite, and a little calcite in some of the veinlets.

their iron content, most varieties yield an abnormally red soil. Some varieties, however, contain little iron and are pale yellow or white. In the colored varieties where indications of post-depositional change are seen, the oxidation state of the iron has changed from an original red oxidized state to a green reduced state. Locally, leaching of the iron by hydrothermal solutions has bleached colored cherts to a chalky white color.

Most of the chert is accompanied by shale, which is usually of the same color, and a rhythmic interlaying of the hard chert and soft shale is characteristic. Chert layers are generally from ½ to 4 inches thick, and average about 2 inches; the shale interlayers are generally much thinner, and average less than a quarter of an inch. Less commonly the chert occurs as massive beds without shale partings. Such massive beds are generally only a few feet thick and occur within or above sequences of rhythmically layered chert and shale. However, exceptionally massive beds of chert attain a maximum thickness of 40 feet in the Ladd-Buckeye mine area, Carbona quadrangle (Trask and Pierce, 1950). Most massive beds are of white or pale color, and it is likely they owe their massive character to the absence of the iron and aluminum minerals that normally form the shale partings.

A chert-shale sequence normally forms a lenticular entity that does not include even thin interbeds of graywacke, black shale, or volcanic material. Such chert-shale lenses range in length from a few feet to as much as 3 miles in the unusual occurrences of the Ladd-Buckeye area, but generally they cannot be traced for more than a few hundred feet. Their range in thickness is equally great, being from a foot or less up to a reported thickness of more than 1,000 feet in the Ladd-Buckeye area, but a typical thickness is only about 30 feet. Sections reported to be very thick commonly prove to be made up of several different chert-shale lenses that may or may not be separated by other kinds of rock. Breadth-to-thickness ratios of individual chert-shale lenses are generally on the order of about 15 to 1.

Davis (1918a) recorded many critical observations regarding the rhythmically bedded cherts, and some of these are repeated here because of their bearing on the origin of the chert-shale lenses. As he indicated, good exposures of the thin-bedded chert give a first impression of an orderly sequence of thin beds with great lateral continuity, but a more detailed examination reveals that what appear to be continuous beds of chert are actually thin lenses or discs with a continuity of only a few feet to a few tens of feet. Furthermore, the lenses generally do not taper consistently from the center to extremity, but instead they maintain a more or less constant thickness to within a few inches of their margin and then wedge out abruptly. In some cases only one surface may be irregular and thus cause an abrupt pinching or swelling, and commonly the adjacent layer has a compensatory swell or pinch. The shale partings also may exhibit similar change in thickness, though these changes are not so obvious because the partings are so thin. It is not uncommon for a shale parting to terminate abruptly so that the overlying and underlying chert beds merge into one.

The relations of the composite chert-shale lenses to laterally equivalent rocks along strike are generally obscure, and the mode of termination of lenses must be largely deduced from scattered spot observations. Many lenses that overlie greenstone and are overlain by graywacke seem to merely cap the greenstone and wedge out laterally; other lenses are surrounded by graywacke and shale and were deposited as a unit within the sedimentary sequence. Curiously, the cherts do not interfinger with the graywacke, nor do the red or green shales that accompany the chert grade into the normal black shales that are a part of the graywacke sequences. Detrital grains of quartz or feldspar, similar to those of the graywacke, do not occur in cherts and only rarely do the accompanying shales contain a sprinkling of minute angular fragments of quartz, feldspar, or chlorite. Although chert-shale lens terminations are difficult to observe, it is quite

Table 9. Analyses of Franciscan cherts, with a chert from the Knoxville Formation near Stanley Mountain.

	1	2	3	4	5	6	7	8	9
SiO_2	93.54	93.5	95.9	94.7	93.0	97.4	96.5	95.1	84.9
TiO_2	n.d.	0.04	0.06	0.06	0.12	0.03	0.08	0.06	0.18
Al_2O_3	2.26	0.96	1.1	1.1	2.0	0.47	1.5	1.2	4.8
Fe_2O_3	0.48	2.8	1.7	2.7	2.4	1.3	0.34	1.9	2.1
FeO	0.79	[a]	0.34	0.22	[a]	0.26	0.38	0.2	1.8
MnO	0.23	1.3	0.05	0.05	0.40	0.02	0.03	0.31	0.46
MgO	0.66	0.11	0.10	0.14	0.13	[a]	0.16	0.11	1.2
CaO	0.09	0.42	0.50	0.06	0.11	0.05	0.17	0.22	0.46
Na_2O	0.37	0.01	0.02	0.01	0.11	0.01	0.11	0.04	0.70
K_2O	0.51	0.08	0.26	0.37	0.41	0.04	0.26	0.24	0.31
H_2O+	0.72	0.72	0.70	0.63	1.0	0.55	0.65	0.61	2.0
H_2O-	0.21	0.22	0.11	0.16	0.26	0.07	0.15	0.16	0.72
P_2O_5	n.d.	0.03	0.02	0.03	0.05	0.04	0.04	0.04	0.02
Total	99.86	100.2	100.9	100.2	100.0	100.2	100.4	100.2	99.7

1. Brownish-red chert from head of Bagley Canyon, north side of Mount Diablo, Contra Costa County, Calif. (Turner, 1891, p. 411). Analysis by W. H. Melville.

2 7, 9. By rapid rock analysis method described in U. S. Geol. Survey Bull. 1036-C. Analyses by P. L. D. Elmore, S. D. Botts, I. H. Barlow, and Gillison Chloe.

2. Franciscan thin-bedded red chert (60-800) from roadcut on west side of northern peak, Twin Peaks, San Francisco, Calif.

3. Franciscan thin-bedded chert (60-802), red with some greenish-white borders where adjacent to green shale, 400 ft east of U. S. Highway 101 on north side of Sausalito lateral, San Francisco North quadrangle, Marin County, Calif.

4. Franciscan thin-bedded red chert (SF-1970) on Sausalito lateral 3,000 ft northwest of Yellow Bluff, San Francisco North quadrangle, Marin County, Calif.

5. Franciscan thin-bedded red chert (SF-2145), 600 ft east of 16th Avenue and 1,100 ft north of Ortega Street, San Francisco, Calif.

6. Franciscan red chert (SF-2143) forming massive bed about 25 ft thick, 600 ft east of 16th Avenue and 500 ft north of Ortega Street, San Francisco, Calif.

7. Franciscan thin-bedded green chert (SF-2043), west side of U. S. Highway 101, at a point 8,500 ft northwest of Yellow Bluff, San Francisco North quadrangle, Marin County, Calif.

8. Average of 2 7.

9. Knoxville thin bedded reddish-brown chert (B 28) from north side of Alamo Creek Canyon, a quarter mile west of east edge of Nipomo quadrangle, 1 mile north of Stanley Mountain, San Luis Obispo County, Calif.

[a] Reported as < 0.05.

clear that the composite lenses thin by a decrease in the number of rhythmically layered beds rather than by a decrease in the thickness of the individual layers. The central part of chert-shale lens may be made up of hundreds of chert layers several inches thick, whereas near its edge the lens contains only a few layers, but they are of similar thickness.

Many exposures of rhythmically bedded chert show small-scale effects of deformation. Among the most common are sharply pointed chevron folds which may occur in limited zones involving a few dozen beds and do not carry through to the beds above or below. Generally the sharply bent axial portion is unbroken, which has led to the suggestion that such folds develop as a result of submarine slumping prior to the final hardening of the layers.

Nearly all rhythmically bedded cherts are cut by many fractures oriented at right angles to the layering, and as seen on the layer surfaces these fractures usually are in two sets, forming a rhomboid fracture pattern. In many places the fractures have been filled with quartz, which contains less iron than does the chert and is lighter in color. Normally neither fractures nor veins extend through the shale partings between chert layers, and there is little correspondence between fractures in adjacent layers.

Silica-filled Radiolaria are so common that these rocks are often referred to as "radiolarian cherts," but not all specimens contain Radiolaria. Where present in the red cherts the Radiolaria are readily visible with the aid of a hand lens as small, round or conical, clear areas. In green or white cherts they seem to be equally as abundant but are not so readily recognized because they show little contrast to the rest of the rock. Radiolaria may, in exceptional cases, amount to more than half of the chert, but in the average chert they probably amount to less than 10 percent. The shales accompanying the cherts also contain Radiolaria, but in them Radiolaria do not seem to be as abundant as in the more siliceous rock.

Microscopic features. Thin sections of unmetamorphosed chert generally show a fine aggregate of quartz and chalcedony, which in the common red varieties is clouded with red iron oxide dust. Silica-filled tests of Radiolaria are free of iron and stand out in contrast to the cloudy matrix. Where they are well preserved their borders show sharp spines and their interiors may show a delicate mesh structure, but more typically only their general outline can be clearly distinguished. The silica within the Radiolaria may be mosaic quartz, a little coarser than in the surrounding rock, or it may consist of radial fibers of chalcedony. Opal has not been found in the cherts; however, some cherts are composed of silica that is virtually isotropic but with an index slightly greater than that of balsam. No detrital grains of feldspar, quartz, or other minerals have been identified, though some sections show a few scattered shreds of a pale-brown material that appears to be altered mafic glass, probably now converted to a

Table 10. Analyses of Franciscan shales accompanying cherts, with analyses of some other shales for comparison.

	1	2	3	4	5	6	7	8	9	10	11
SiO_2	69.98	50.58	40.1	60.9	58.4	66.7	66.3	58.5	63.2	58.51	54.48
TiO_2	n.d.	0.55	0.76	0.92	0.66	0.81	0.76	0.78	0.71	0.66	0.98
Al_2O_3	11.69	14.35	10.9	13.1	14.3	14.1	15.9	13.7	15.7	15.55	15.94
Fe_2O_3	6.23	15.64	27.6	9.2	7.4	6.5	3.3	10.8	1.3	4.03	8.66
FeO	1.08	0.65		1.0	--	0.58	0.96	0.33	4.7	2.50	0.84
MnO	0.49	0.36	4.8	0.11	1.4	0.10	0.08	1.30	0.08	tr	1.21
MgO	1.29	3.08	3.5	2.3	3.3	1.6	1.8	2.5	3.0	2.44	3.31
CaO	0.38	1.77	0.53	--	2.0	0.05	0.05	0.53	1.5	2.99	1.96
Na_2O	0.73	0.70	0.12	0.08	1.7	0.10	0.18	0.44	2.1	1.28	2.05
K_2O	3.72	3.84	4.5	4.9	3.9	3.8	4.9	4.40	2.4	3.28	2.85
H_2O+	2.92	5.19	4.8	4.6	3.1	4.0	4.3	4.2	3.7	3.69	7.04
H_2O-	1.03	3.30	2.2	2.0	2.0	1.2	1.3	1.8	0.52	1.31	
CO_2	--	--	0.08	--	--	--	--	--	--	2.51	--
P_2O_5	0.05	n.d.	0.14	0.14	1.3	0.09	0.27	0.38	0.18	0.17	0.30
Total	99.59	100.01	100.0	99.2	99.5	99.6	100.1	99.7	99.1	98.92	99.62

1. Franciscan brownish-red shale from head of Bagley Canyon, north side of Mount Diablo, Contra Costa County, Calif. (Turner, 1891, p. 411). Analysis by W. H. Melville.
2. Franciscan red shale from Red Rock Island in San Francisco Bay, Contra Costa County, Calif. (Lawson, 1914, p. 23). Analysis by Irving Miller. "Soluble" of 0.38 given in original analysis omitted here.
3-7. By rapid rock analysis method described in U. S. Geol. Survey Bull. 1036-C. Analyses by P. L. D. Elmore, S. D. Botts, I. H. Barlow, and Gillison Chloe.
3. Franciscan red shale (60-801) interlayered with chert (no. 2, table 9), from roadcut on west side of northern peak, Twin Peaks, San Francisco, Calif.
4. Franciscan green shale (60-803) interlayered with chert (no. 3, table 9), 400 ft east of U. S. Highway 101 on north side of Sausalito lateral, San Francisco North quadrangle, Marin County, Calif.
5. Franciscan red shale (SF-2111) in 1-foot thick bed interlayered with chert, east side of U. S. Highway 101, 3,750 ft west of Yellow Bluff, San Francisco North quadrangle, Marin County, Calif.
6. Franciscan red shale (SF-2145A) interlayered with red chert (no. 5, table 9), 600 ft east of 16th Avenue and 1,100 ft north of Ortega Street, San Francisco, Calif.
7. Franciscan green shale (SF-1941) in 1-foot thick bed below massive chert (no. 6, table 9), 600 ft east of 16th Avenue and 500 ft north of Ortega Street, San Francisco, Calif.
8. Average of 3-7.
9. Average of four Franciscan shales interbedded with graywacke (no. 5, table 3).
10. Average of 78 shales calculated from composite of 51 Paleozoic shales and 27 Mesozoic and Cenozoic shales given by Clarke (1924, p. 552).
11. Composite of 51 samples of deep sea "red clay" (Clarke, 1924, p. 518). Analysis by G. Steiger with special determination by W. F. Hillebrand and E. C. Sullivan. Omitted here are a dozen minor oxides; Mn given as MnO_2.

chlorite. Thin veins of sutured quartz are common, and in some specimens these are partly replaced by calcite.

Chemical features. Chemical analyses of the cherts given in table 9 indicate that the silica content ranges from 93 to more than 97 percent. Most of the rest is alumina and ferric iron, representing an admixture of the same materials that form the shale parting layers. The alkalies are in all cases low, with potash consistently much greater than soda.

An analysis of a chert from a part of the Knoxville Formation that contains greenstones and chert in the Nipomo quadrangle is also given in column 9 (table 9). This chert is reported to be similar to the Franciscan chert and is one of the indications of the reported gradual transition from the Franciscan into the Knoxville (Taliaferro, 1943a, p. 197-200). However, this chert has both physical and chemical features that are not typical of Franciscan chert. In outcrop it is better bedded, does not show as sharp breaks between chert and shale, and does not exhibit the lenticularity of beds typical of the rhythmically bedded Franciscan chert. In thin section it can be seen to contain many minute detrital grains of quartz and feldspar which are rare in the Franciscan cherts. Chemically it contains much less silica and has a content of soda that is twice that of potash.

Shales associated with Franciscan cherts are distinctly different from shales that occur interlayered with graywacke. As has been mentioned, the shales with cherts are generally colored red or green, matching the color of the cherts with which they occur, whereas the more normal Franciscan shales are gray or black. The red color is due to the abundance of goethite, or in some cases hematite. X-ray diffraction analyses by Schlocker (oral communication, 1963) indicate the presence of considerable mica, most of which is poorly crystalline, and moderate amounts of a chlorite-like mineral and quartz, as well as the goethite and hematite. Shreds of altered mafic glass can also be seen in some thin sections.

Chemical analyses of the shales accompanying the cherts are given in table 10, along with averages of the normal Franciscan shales, average shale, and average deep-sea "red clay" for comparison. Chemically the shales that accompany the Franciscan cherts differ markedly from the normal Franciscan shales in having an extraordinarily high K_2O Na_2O ratio of about 10 instead of about 1, and in having much more iron and also a higher ferric/ferrous ratio. Shales accompanying cherts compare more closely with the oceanic "red clay" deposits, but they have a much higher K_2O/-Na_2O ratio than the open ocean deposits.

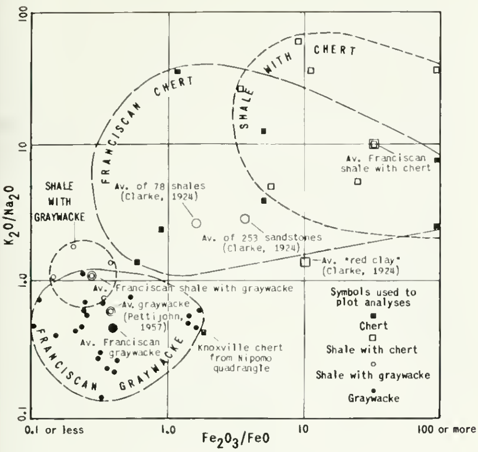


Figure 14. Log plot of K_2O/Na_2O and Fe_2O_3/FeO ratios in graywackes, shales, and cherts.

A further difference between the shales with chert and shales accompanying graywacke is found in the manganese content, which is appreciably higher in the shales with the chert.

The main differences between the two kinds of shales in the Franciscan are well brought out by plotting the K_2O/Na_2O ratio against the Fe_2O_3/FeO ratio as shown on figure 14. In this figure, which is prepared on a Log Log base, the area of the normal gray or black shales of the Franciscan overlaps the area of Franciscan graywacke, whereas the area that encompasses the shales occurring with chert overlaps much of the Franciscan chert field. Also shown is the difference in position of the average "red clay" of the deep-sea and the Knoxville chert from the Nipomo quadrangle.

Origin. The origin of the Franciscan cherts has been discussed by Davis (1918a), Taliaferro (1933, 1943a), and Trask and Pierce (1950), but there is no universal agreement either on how they were formed or the depth at which they were deposited. Early ideas, admirably summarized by Davis (1918a), were that the cherts were radiolarian oozes deposited at abyssal depths, because only in the deeper parts of the oceans were such oozes known to be accumulating. Davis, however, believed the graywackes of the Franciscan were largely continental deposits and so could not support the abyssal origin hypothesis; he concluded that the cherts were deposited by siliceous hot springs arising from the mafic volcanics. Taliaferro also ascribes the origin of the cherts to either siliceous springs or reaction of the lava with sea water, but, largely because of the presence of conglomerates layered with the graywacke, he envisioned a shallow-water origin for all the formation, including the cherts. As will be explained in the following sections, we believe that most of the cherts and accompanying shales owe their origin to reactions between hot lava and sea water, and that these reactions must have taken place at depths comparable to the average depth of the oceans in order to have yielded the quantities of silica represented by the chert.

The general occurrence of the chert-shale lenses in the assemblage of Franciscan rocks in close association with greenstone, and the frequency with which these lenses are found immediately above the greenstone, strongly supports the concept that the cherts somehow owe their origin to the volcanic eruptions. A similar association is found in many other eugeosynclinal assemblages throughout the world and has led geologists working in these areas to similar conclusions. Other kinds of chert, however, are found in different environments and are not associated with mafic volcanic rocks. Thus, while our ideas regarding the origin of the Franciscan cherts might apply to cherts in other eugeosynclinal assemblages, they certainly cannot be extended to include all chert sequences, such as, for example, the widespread and well-known cherts of the Monterey and Phosphoria Formations.

As the greenstones in the Franciscan represent submarine eruptions, it is attractive to postulate that the cherts resulted from reactions between hot lava and sea water at the time of the eruptions. Because the lavas do not occur as massive flows but rather as pillow lavas, pillow breccias, breccias, and tuffs, optimum conditions were present for such reactions to take place during the submarine eruptions. Assuming that reaction did take place, it is difficult to ascertain what the effects would be in terms of materials dissolved in the water or lost from the congealing magma. Van Hise and Leith (1911) and Krauskopf (1956a) found experimentally the solubility of some of the constituents of basalt in sea water at low temperatures and pressures, but apparently no experimental work involving these reactions has been done at even moderately high temperatures and pressures. Thus one must look for indirect evidence regarding the materials that might be dissolved by sea water reacting with molten or still hot lava during a deep-sea eruption. Two lines of approach can be used: (1) extrapolation of experimental data on the solubility at elevated temperatures and pressures of the major chert-shale components, particularly silica; and (2) inferences based on chemical analyses of greenstones, particularly pillows, which may indicate what components are lost by the magma while reacting with sea water.

The problem of forming chert in a marine environment by inorganic means is largely a problem of silica concentration. The oceans of the world today, as probably always in the past, are much undersaturated

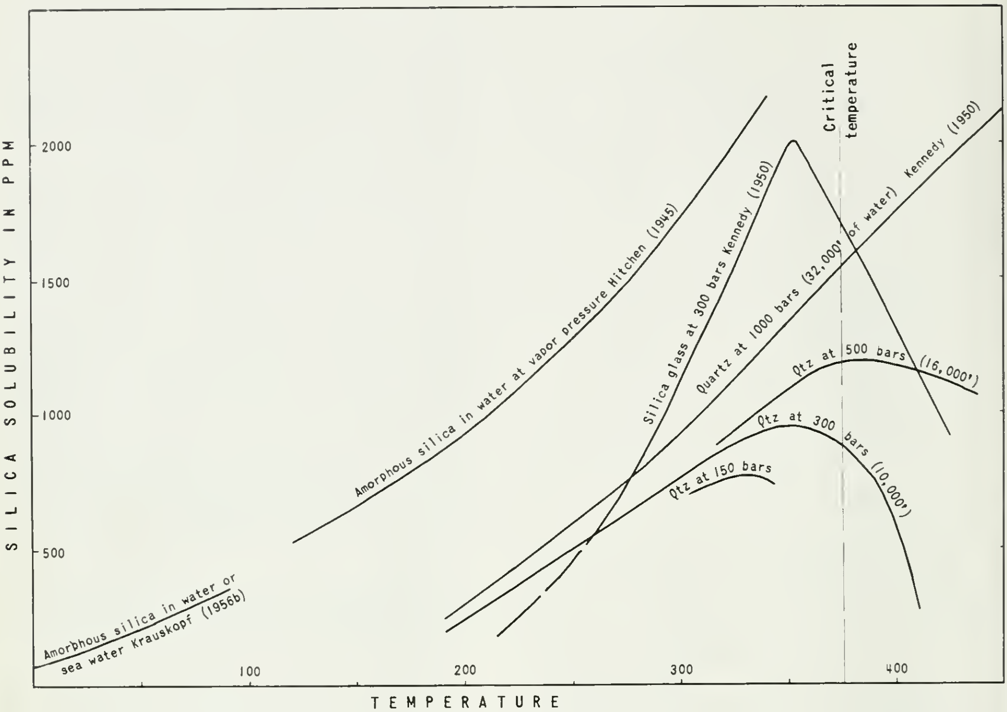


Figure 15. Solubility of various forms of silica in water.

with respect to silica. They normally contain less than 10 ppm, whereas saturation with respect to silica gel is about 100 ppm at 25°C and about 70 ppm at 5°C (Krauskopf, 1956b, p. 13; 1959). A reaction between hot lava and sea water could locally raise the silica concentration in the water above the normal content, but to bring about the inorganic precipitation of silica to form chert requires increasing the silica concentration considerably above saturation, with respect to a precipitating phase, in order to effect rapid and abundant precipitation. At shallow depths, where water is converted to steam at only 100°C or a little more, water saturated at this temperature would, when cooled to normal oceanic temperature, be supersaturated at the most only 300 to 500 percent with respect to amorphous silica. It is unlikely, therefore, that lava either flowing into the sea or being erupted at a shallow depth will cause the inorganic precipitation of much silica. At abyssal depths, however, the water pressure has the double effect of raising the boiling point and notably increasing the solubility of silica. In the absence of directly applicable experiments using sea water, we may turn to the results of Hitchen (1945) and Kennedy (1950) for data on the solubility of various forms of silica in pure water. At elevated temperature, sea water may be more reactive than pure water, but Krauskopf (1956b, p. 13) has found the solubility of amorphous silica in pure water and in sea water at low temperatures to be about the same. Figure 15 shows the solubility of various forms of silica through the range of temperatures and pressures that we believe may apply to the formation of Franciscan chert. The temperature of the reactive interface between the basaltic magma and deep sea water can be calculated to be in the order of 350°C. As is indicated by figure 12, at a depth of 13,000 feet, which is an average figure for the Pacific Ocean floor, and at 350°C the solubility of quartz in sea water is about 1,000 ppm, whereas the solubility of amorphous silica or silica glass under the same conditions is about 2,000 ppm. Either magma or the quenched glass at the reactive interface would be probably at least as soluble as silica glass, but in the absence of experimental data obtained from conditions that closely approximate those postulated, the figures given must be regarded as only indicative. They suggest, however, that large

amounts of silica can be added to sea water by reaction and solution during a submarine volcanic eruption.

That reactions between mafic lavas forming the Franciscan greenstones and sea water actually have taken place is best indicated by the chemical differences between the cores, rims, and matrices of the pillow lavas, and it is further supported by the consistent chemical differences between intrusive (?) diabasic rocks and pillow or fragmental greenstones resulting from submarine eruptions. As is set forth on pages 50 et seq., and especially in tables 5, 6, and 7, the analyses now available indicate that the magma lost to the sea water large amounts of silica, alumina, lime, and soda, and smaller amounts of iron. To ascertain if sufficient silica has been lost from the mafic magma to form the chert requires not only knowledge of the amount lost by a unit volume of magma but also the ratio of the amount of chert to the amount of magma. The ratio of chert to greenstone varies widely in the Franciscan assemblage and cannot be determined accurately on the basis of existing geologic maps. The outcrop area of chert is greatly exaggerated on most maps because of the small size of many of the outcrops relative to the map scale, and because fragments of chert are so resistant to weathering that they travel far downslope, thereby leading to an overestimation of the actual size of the chert body. In the New Almaden district, where the distribution of chert and greenstone was mapped in detail, we found a ratio of chert to greenstone of 1:250. On the other hand, measurements made on maps of seven quadrangles in the San Francisco Bay area gave a chert to greenstone ratio of 1:5. Although the New Almaden area may not be typical, from what we have seen of the Franciscan terrane it seems likely that a realistic ratio for most of the Franciscan is closer to 1:250 than 1:5. If the ratio is about 1:100, and the average silica content of the greenstones is about 50 percent, to derive the silica present in the cherts of the Franciscan would require a loss of only 2 percent of the silica in the indicated amount of mafic magma, assuming all the silica given up by the magma is redeposited as chert. Although there is considerable doubt as to what amounts of silica, and also alumina and iron, are lost from the magma by reaction, the analyses of the pillow lavas indicate the quantities are more than adequate to account for the chert-shale sequences even under the most unfavorable interpretations of the analytical data.

Assuming that silica, alumina, and iron have been added to the deep sea water by reaction with magma, it is still necessary to have a mechanism for precipitation and deposition if the cherts are to be explained by such a hypothesis. Experimental data indicates that at a depth of 13,000 feet and a temperature of 350 C ocean water heated by lava might become charged with perhaps 2,000 ppm of silica. Such hot silica-rich water will of course rise rapidly, and additional water will flow in from the side to take its place. Thus above an active submarine eruption a rising column of warm water will be formed, and as the water rises it will be cooled until its silica content will far exceed the 100 ppm required for saturation at normal surface temperatures. Although there is a strong tendency for silica-bearing solutions to remain supersaturated if the dissolved silica is not far in excess of that required for saturation, the silica concentration suggested above is undoubtedly great enough for the silica to be polymerized and precipitated as gelatinous silica, which would then rain down onto the sea floor. Iron and alumina, and perhaps in some cases manganese also, should behave much the same as silica and can be expected to be precipitated along with the silica gel. The net result is an accumulation on the sea floor of a mass of silica gel with impurities, which subsequently, by a process to be suggested, is changed to form an entire chert-shale lens consisting of dozens or hundreds of layers. Quantitatively the mechanism seems capable of yielding a lens a few tens of feet thick, but without a secondary collection process, such as accumulation by flowage into a basin area on the sea floor, this mechanism seems incapable of yielding lenses more than 50 feet thick, because of limitations on the amount of water that can be heated and on the quantity of silica that can be dissolved in the heated column of water.

With this origin a composite chert-shale lens must accumulate rapidly as a result of a single submarine eruption, and thus an explanation is provided for the absence of detrital grains in the chert and for the lack of marginal interdigitation of the chert or ferruginous shale beds with beds of graywacke or black shale. The presence of Radiolaria in the cherts is best explained by the abundance of silica in the water, thus resulting in a rapid multiplication of the Radiolaria, and a general sweeping of the water column by the precipitating silica gel. The apparent oxidized condition of the hydrated iron oxides is accounted for because this is the form in which the iron can be expected to precipitate.

If an entire chert-shale lens initially accumulates as a mass of iron-laden silica gel, then the rhythmic layering into what superficially appear to be beds needs to be explained. It seems likely that the layering is brought about by a diffusion effect during the conversion of the silica gel to opal, which later crystallizes to form quartz. The iron and aluminum hydroxides are apparently expelled during this process and collect to form the shale layers. This mechanism was suggested by Davis (1918a) in his attempt to explain the origin of the layers and account for some of their unusual features which are not readily explained by normal layer-by-layer deposition. In support of his theory he points out that he was able to experimentally reproduce in a beaker the layering and the lensing-out of layers. This was done by mixing sodium silicate and finely divided red Franciscan shale and then inducing

Figure 16. Map showing distribution of Franciscan limestone.

flocculation of gelatinous silica by carefully adding ammonium carbonate to the top of the suspension. He obtained, though on a small scale and in limited number, a series of thin bands of red shale and clear silica gel that had many of the features of the rhythmically layered cherts.

Other varieties of chert. In addition to the typical bedded cherts, the Franciscan also contains two uncommon varieties that are mentioned for the sake of completeness. One of these has a red-brown color because of an abundance of iron oxides, but it differs from the bedded chert in that it occurs only in curious, small, mammilary or botryoidal masses, many of which have distinctive internal structures. Some that are generally only a foot or two in diameter are crudely spherical and have a surface of arcuate mammilary bumps; other masses that range in size up to 20 feet consist of a series of botryoidal, cauliflowerlike lumps packed together in a most irregular fashion. Some individual lumps exhibit no primary internal structure; others consist of an aggregate of superimposed upright hemispheres about an inch in diameter. A secondary internal structure seen in many of the mammilary cherts consists of white quartz-filled or drusy arcuate openings that clearly are the result of dehydration cracking and later filling by the addition of iron-free quartz. Because these small mammilary masses are so much harder than most of the other Franciscan rocks, they generally are found as float or as protruding knobs on a soil-covered hillside. Therefore, there are few data available regarding the relation of these masses to other rocks. Some of the mammilary masses reported by Davis (1918a) clearly occur as inclusions in "gabbro," and others have been seen along presumably intrusive greenstone contacts or on greenstone at the base of a pile of rhythmically bedded chert. Those masses that show dehydration cracking probably originated when incompletely dehydrated silica gel was heated either by intrusive magma or by coming to rest on still warm, but not molten, lava.

The other variety of chert found in the Franciscan Formation is restricted in occurrence to beds of limestone. Where it occurs with black or white limestone, this chert is dark to pale gray, but where it occurs in pink limestone, the chert is also colored pink or red by finely divided iron oxides. Typically this kind of chert is found in small nodules or short lenses, but locally it is abundant enough to form thin beds which alternate with the limestone beds.

LIMESTONE

Limestone is rare in the Franciscan eugeosynclinal assemblage and constitutes less than 0.1 percent of the total volume of sedimentary rock. Most exposures of limestone lie east of the San Andreas fault and within a narrow, northwesterly trending belt which extends from the San Juan Bautista quadrangle in the south to the Scotia quadrangle in the north (fig. 16). Between the Scotia quadrangle and Oregon no limestone has been found, but a similar limestone, designated the Whitsett Limestone Lentils by Diller (1898), occurs near Myrtle Creek, Oregon. Limestone is virtually unknown in the Diablo Range and in the entire eastern half of the northern Coast Ranges. In the southern Coast Ranges, west of the Nacimiento fault, limestone apparently occurs in the Franciscan only as a few small lenses. Page, Marks, and Walker (1951, p. 1732) report discontinuous lenses less than 2 feet thick in the Franciscan northeast of Santa Barbara, and Taliaferro (1943a, p. 144) mentions the presence of red algal limestone interbedded with chert in the western part of the Adelaida quadrangle, San Luis Obispo County. These southern limestones are poorly known and have yielded no diagnostic fossils; their relation to other Franciscan limestone has not been established.

The most extensive development of Franciscan limestones is found on the San Francisco peninsula (Lawson, 1914; Walker, 1950), where the beds are thickest and exposures most continuous. The limestone occurs as isolated masses in a linear belt extending from Rockaway Beach on the Pacific Ocean coast southeastward for a distance of about 10 miles, where it is truncated by the San Andreas fault. On the east

Photo 33. Calera type of limestone with chert nodules. Llagas Creek, Morgan Hill quadrangle.

side of the fault, the limestone recurs about 16 miles to the south on Black Mountain in the Palo Alto quadrangle, and it continues southward as isolated exposures into the northern part of the San Juan Bautista quadrangle. On the San Francisco peninsula the limestone is extensively quarried for cement and crushed rock for road materials and aggregate, but elsewhere most masses are smaller, and have more limited economic potential.

Exposures of Franciscan limestones are elongate or lenticular masses from a few feet to as much as a mile in length and from several feet to 400 feet or more in thickness. Most are small, isolated masses only a few feet thick. Some of the lenticularity of the limestone bodies can be ascribed to tectonic dislocations, but initial deposition of at least some of them was as small lenses, and beds with a depositional continuity of over a mile were probably uncommon. The isolated masses do not everywhere lie at exactly the same stratigraphic horizon, but their fossil content indicates that all were deposited during only a brief part of the time spanned by the deposition of the entire assemblage of Franciscan rocks.

Several different types of limestone have been recognized, but the most common kinds are a white-weathering, light- to dark-gray type which Lawson (1902, p. 416; see also Lawson, 1914) named the Calera Limestone, and a pink to deep-red laminated limestone which is best known from exposures near Laytonville in the northern Coast Ranges. These two types of limestones generally do not occur together, but they are nearly of the same age. We herein refer to the red limestone as the Laytonville-type limestone and the white as the Calera-type, as exact correlation of the various masses cannot yet be made.

Chert is commonly associated with Franciscan limestones and in places constitutes 30 percent or more of the total volume. It occurs both in lenticular beds and as isolated, generally loaf-shaped nodules (photos 33 and 34). Chert associated with the iron-poor Calera-type limestone ranges in color from light gray to black and is usually highly fractured and cut by many thin veins. The chert that occurs with the Laytonville-type limestone is generally red, as both it and the limestone contain goethite. The red cherts with the limestone locally contain Radiolaria and seem to be similar to the typical rhythmically layered Franciscan cherts that are closely associated with greenstones.

Calera type of limestone. The Calera Limestone was named by Lawson (1902, p. 416) for exposures in sea cliffs at the lower end of Calera Valley, San Mateo County. It was later relegated by Lawson (1914) as the basal member of his Cahil Sandstone. As typically developed, this limestone is dense, aphanitic, massively bedded, and locally it contains abundant Foraminifera. Its color ranges from light gray to bluish gray to nearly black, with lighter shades predominating. Locally, some beds have a light-pink to flesh or salmon color, but none are deep pink or red. At its type locality near Rockaway Beach on San Francisco peninsula, the Calera Limestone Member of the Franciscan Formation forms a lens-shaped body at least 200 feet thick, which Miranda (1947) subdivided into five alternating zones of gray and black limestone. The gray limestone units are very fine grained, well bedded, cut by many thin calcite veins and contain abundant Foraminifera (photos 35, 36, and 44). The black limestone units have thinner beds, fewer calcite veins, fewer Foraminifera, and a coarser grained, granular texture.

Photo 34. Calera type of limestone with interbedded chert layers (dark gray), Permanente Cement Co. quarry, Palo Alto quadrangle.

On being struck with a hammer, the black limestone emits a strong bituminous odor.

Farther south in the quarries of the Permanente Cement Co., near Los Altos in the Palo Alto quadrangle and in scattered outcrops in the New Almaden area, a limestone like the Calera is divisible into an upper light-colored, foraminiferal unit and a lower bluish-gray unit in which Foraminifera are rare or absent. In the southern part of the Permanente quarry, the upper light-colored unit is split into two members by an intervening basaltic layer (photo 37). Based on information supplied by Mr. Don Towse, geologist, Permanente Cement Co., a generalized stratigraphic section of the limestone in the Permanente quarry is as follows:

Stratigraphic unit	Thickness (in feet)	Average $CaCO_3$ content of bulk samples that include interbedded chert (in percent)
Upper "white" limestone	130	75
Basalt	90	
Lower "white" limestone	110	50
"Blue" limestone	160	87

Fault contact with Franciscan volcanic rocks.

Glauconitic limestone occurs in the New Almaden area as small, isolated masses. This limestone is coarsely crystalline, contains numerous lenses and pellets of glauconite, and lacks interbedded or nodular chert and Foraminifera. It appears to occur stratigraphically above other lenses of light-colored limestone that more

Photo 35. Photamicragraph af Colera type of limestane showing benthonic and pelogic Faraminifero. Note calcite vein displaced by stylolite. Black Mountain, Polo Alto quodrongle.

Photo 36. Photomicrograph of Calero type of limestone from Block Mountain in the Pala Alto quodrangle. Foraminifera are pelogic types ond consist chiefly of globotruncanids and globogerinids.

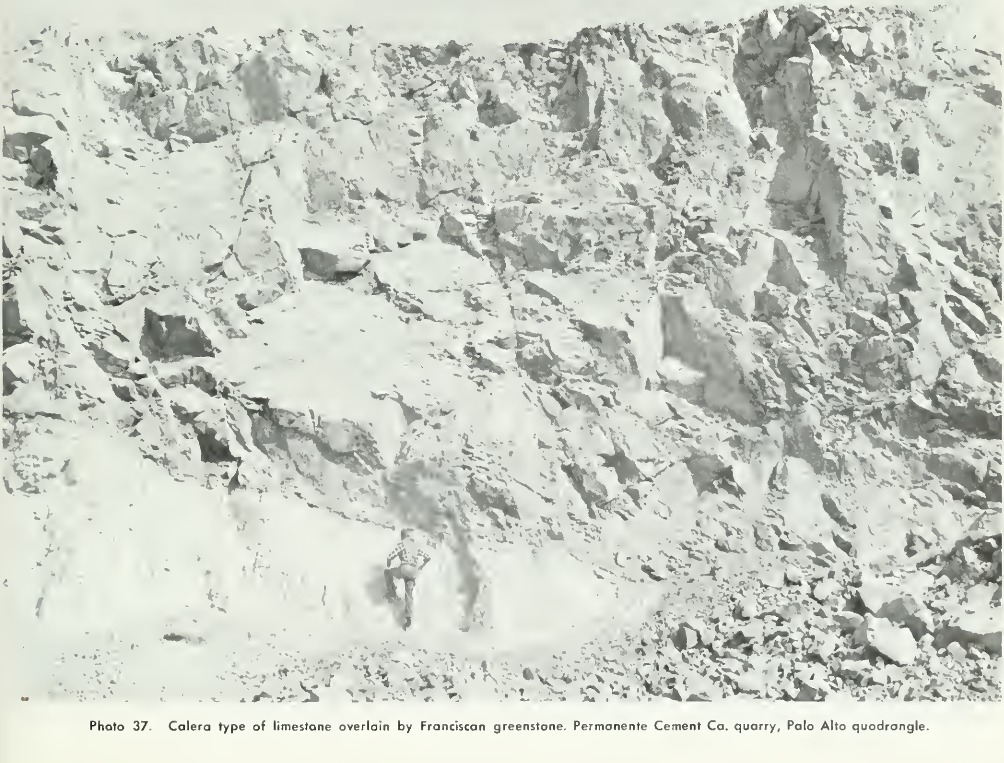


Photo 37. Calera type of limestone overlain by Franciscan greenstone. Permonente Cement Co. quarry, Palo Alto quodrongle.

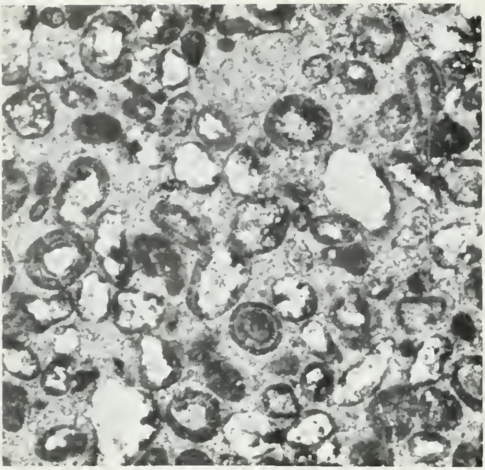


Photo 38. Oölitic Franciscan limestone from Longwall canyon, Los Gatos quadrangle.

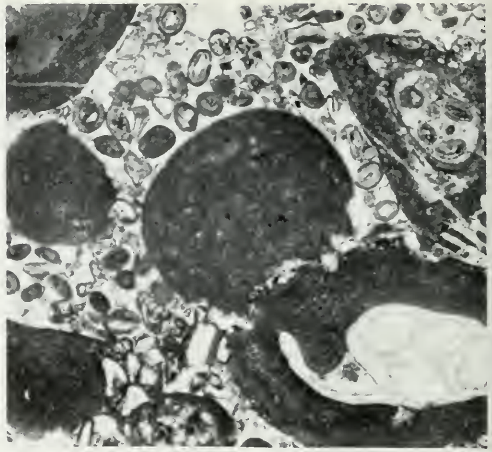


Photo 39. Oölitic Franciscan limestone from Longwall Canyon, Los Gatos quadrangle showing algal (?) pisolites with nuclei consisting of a gastropod and an oölitic lump.

closely resembles the Calera Limestone at its type locality.

Oölitic limestone, apparently a phase of the Calera-type limestone, occurs at one locality south of New Almaden. It is prominently exposed as a few scattered, lenticular beds approximately 50 feet thick and several hundred feet long. The lowest exposed portion is composed of 10 to 20 feet of massive, coarsely crystalline limestone which shows no bedding, current features or any definite traces of organic debris, and the upper portion is oölitic (photos 38 and 39). The oölitic part, however, is not clearly separated into distinct beds but occurs as irregular masses within structureless, crystalline limestone. These oölitic parts exhibit no bedding, channelling, or other evidence of current activity such as is normally associated with oölitic limestones. Most of the oöliths are well sorted and have an average diameter of about 0.3 mm. Their nuclei consist of a variety of material including clear grains of calcite, dense microcrystalline calcite, shell fragments, echinoid plates and spines, fragments of coral, and corroded pieces of volcanic rock. The matrix consists of clear, finely crystalline calcite. The thickness of the oölitic coating varies from the thin skin, consisting of one or two layers surrounding a large nucleus, to many layers surrounding a minute nucleus. The microcrystals of calcite forming the concentric layers are all arranged radially, rather than tangentially as are the aragonite crystals in recently formed oöliths (Rusnak, 1960, p. 471-480).

Locally within this oölitic limestone mass, oöliths of two different-sized groups occur together. Large oöliths, or pisolites, averaging about 2.0 mm in diameter are interspersed in a groundmass of small oöliths averaging about 0.2 to 0.3 mm in diameter (photos 39, 40). The pisolites tend to have irregular concentric layers which are neither as thick nor as sharply defined as those in the small oöliths. Nuclei of the pisolites consist of minute gastropod shells, organic debris including echinoid plates and spines, shell fragments, and algal fragments, together with altered vesicular mafic glass, and aggregates of smaller oöliths. Foraminifera were not observed, either as nuclei or in the matrix, but possibly some of the comminuted organic debris consists of foraminiferal remains. Despite the abundance of fossil debris, only a few relatively well preserved megafossils have been found in this oölitic limestone. These include an echinoid, *Stereocidaris baileyi* Fell, of Late Cretaceous age (see Fell, 1962, p. 29) and a specifically indeterminable specimen of *Nerinea.*

The occurrence of pisolites and oöliths together is anomalous in that most oölitic limestone are very well sorted (Rusnak, 1960; Newell and others, 1960). This association of oöliths of two sizes suggests mixing of material from two different environments or two different modes of formation. Possibly the larger pisolites were formed by algal growth around a nucleus which consisted of organic debris, rock fragments, or oölitic lumps. Similar algal pisolites, formed by *Sphaerocodium bernemanni* Rothpletz, have been illustrated by Hagn (1955, pl. 7). A comparable mixing of small

Photo 40 (opposite). Oölitic Franciscan limestone from Longwall canyon, Los Gatos quadrangle, showing larger algal(?) pisolites in an oölitic matrix.

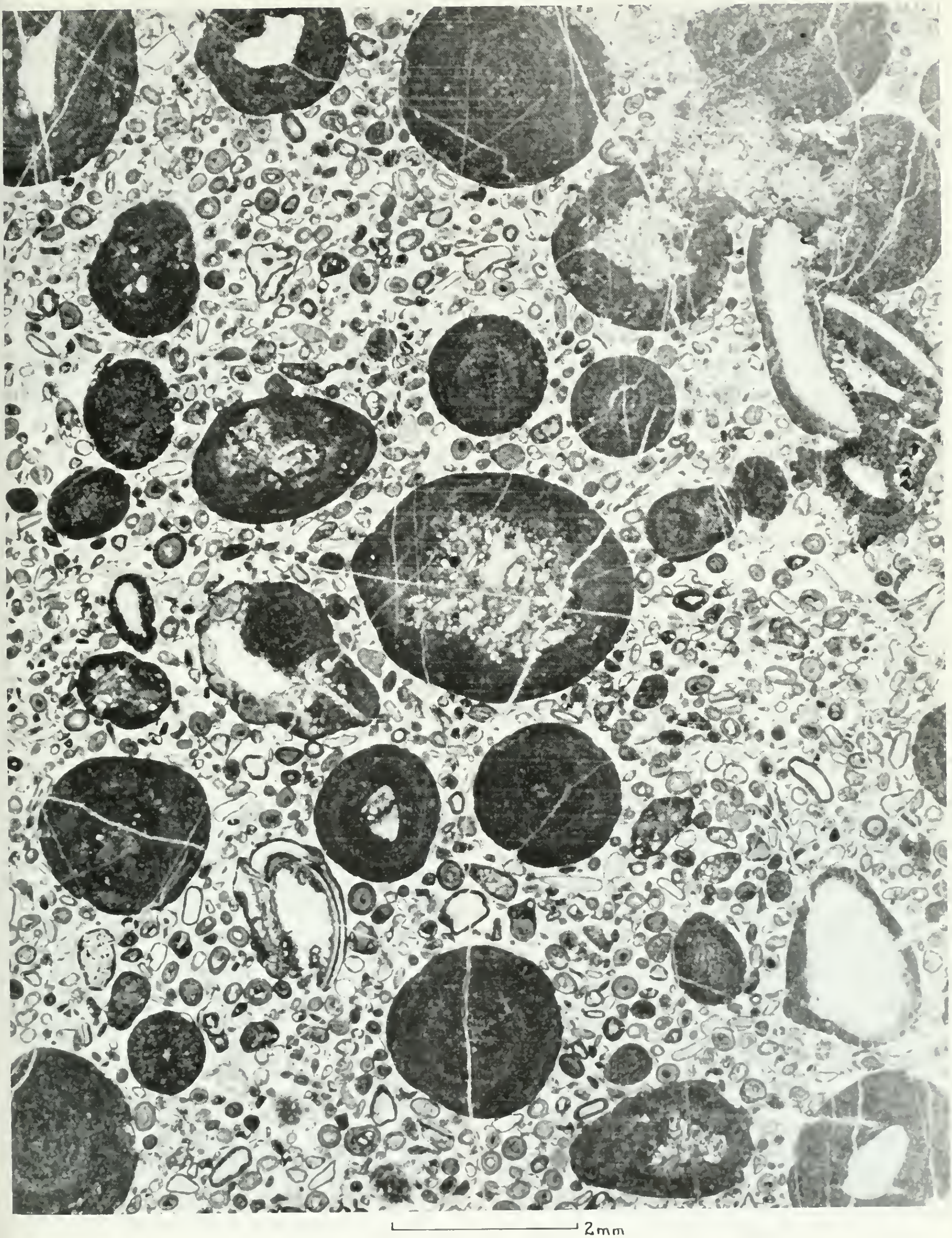

2mm

Photo 41 (above). Organic-detrital, pelletal Franciscan limestone from Fifield Ridge, San Mateo quadrangle, showing pieces of corals and bryozoans.

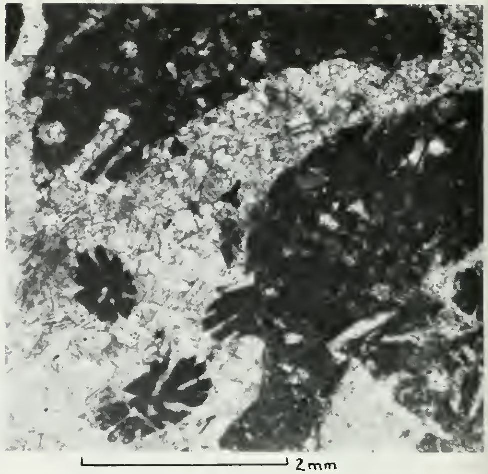
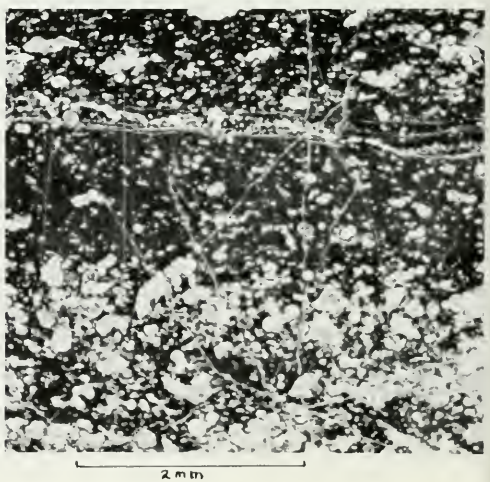


Photo 42 (above). Organic-detrital, pelletal Franciscan limestone from Fifield Ridge, San Mateo quadrangle, showing colonial (hermatypic) corals.

Photo 43 (below). Organic-detrital, pelletal Franciscan limestone from Fifield Ridge, San Mateo quadrangle, showing solitary corals.

Photo 44 (below). Franciscan red limestone (Laytonville-type) from near Annapolis, Skaggs quadrangle, showing Foraminifera (mainly globotruncanids) concentrated in layers.



oöliths and algal pisolites from the Green River Formation of Eocene age is described by Bradley (1929). However, the Green River pisolites differ from the very round Franciscan pisolites in being more irregular with much thicker and less uniform concentric layers.

Perhaps related to the oölitic limestone is an organic detrital limestone that occurs in small amounts at several places on the San Francisco peninsula, notably on Black Mountain west of Palo Alto, on Fifield Ridge west of Crystal Springs Reservoir, and in Permanente Creek below the Permanente Cement Co. quarry (photo 41). This rock consists of rounded grains composed of skeletal material, larger shell fragments, and finely crystalline, elongate, dark-colored pellets set in a clear calcite matrix. The rounded grains average about 0.15 mm in length and about 0.08 mm in width, although there is much variation in shape and size. Identifiable organic material consists of molluscan shell fragments, algal debris, echinoid plates and spines, pieces of bryozoans, and small solitary corals and fragments of probable hermatypic colonial corals (photos 42 and 43).

Laytonville type of limestone. The red, or Laytonville type of limestone is not as abundant as the white Calera-type limestone, and it usually occurs in much smaller and thinner patches. One exposure near Laytonville has a thickness of nearly 100 feet (E. W. Hart, written communication, 1963). Because the red limestone occurs in smaller masses than the Calera-type limestone, and is also less pure, ir has not been regarded as a potential source for cement and has received little study. The red color is due to the presence of ferruginous material, which may constitute as much as 40 percent of the total. As determined by X-ray, this red mineral is chiefly geothite, identical to that found in the red Franciscan chert. In some deposits, the red limestone is well laminated or may show 1-inch color banding, but in others it is massive and shows little or no internal structure. Interbedded red chert commonly occurs with the red limestone. Although the same kinds of Foraminifera are equally abundant in the Laytonville and Calera types of limestone (photo 44), megafossils are unknown in the red variety.

Foraminifera. Locally, Foraminifera are extremely abundant in both the Laytonville and Calera types of limestone, and in some instances as much as 50 percent of the rock is composed of foraminiferal tests. Within the Foraminifera-rich part of the limestone, Foraminifera are scattered throughout the microcrystalline matrix with random orientation and generally with no sign of bedding or of having been sorted. There is no indication that the matrix has been winnowed, with a resulting concentration of the foraminiferal tests. In one specimen of red limestone, however, graded bedding was noted, with large Foraminifera concentrated at the base of each bed and with successively smaller Foraminifera toward the top. Several repetitions of this sequence occur in a single thin section (photo 44). In much of the limestone, however, Foraminifera are lacking, and their absence appears to be a primary feature, as much of the rock consists of very fine grained, microcrystalline calcite that has not recrystallized. The Foraminifera consist predominantly of pelagic forms, including globigerinids and globotruncanids. Benthonic Foraminifera generally are rare, but at one locality, in the New Almaden area, Cushman and Todd obtained a fairly abundant benthonic fauna from a tuffaceous bed interbedded with Calera type of limestone. These forms include: *Gaudryina*, *Pseudoclavulina*, *Arenobulimina*, *Tritaxilina*, *Eponides*, and others.

Chemical composition and insoluble residue. Chemical analyses of the Calera type of Franciscan limestone are given in table 11, and more complete new analyses of the Laytonville type are given in table 11a. The analyses indicates that both types of limestone contain unusually small amounts of magnesium and phosphate. They also show that the red limestone differs from the Calera variety chiefly in its much larger content of ferric oxide, present as goethite, and its larger content of manganese oxide, which is probably present in the form of manganese carbonate.

Insoluble residues, available only for the purer Calera-type limestone, have been studied by Pantin (1946) and Miranda (1947). The material insoluble in HCl averages between 1 and 2 percent and ranges from a low of 0.005 percent to over 20 percent. The residues consist largely of chert, grey and black authigenic silt, and very fine grained quartz sand, but include minor pyrite, barite, garnet, glauconite, organic matter, limonite pseudomorphic after pyrite, and limonite pseudomorphic after microfossils. Authigenic pseudocubic quartz is abundant locally and is particularly common in the oölitic limestone, where it disrupts the concentric layers of oöliths.

Relation of limestone to other rocks. Both the red, or Laytonville-type, and the white-weathering, or Calera-type, limestones generally occur with volcanic rocks, but in most cases, details of the contacts are obscure because of structural complexities or inadequate exposures. Red limestone seems to occur invariably with pillow basalts and is found as matrix separating pillows, draped over the top of masses of pillows, or interbedded with red radiolarian chert in a volcanic rock-chert sequence. The white limestone of the Calera type appears to be most commonly associated with pyroclastic volcanic rocks, rather than with pillow basalts, and thin beds of tuff are locally found interbedded with limestone. In a few places, particularly in the Los Gatos and San Juan Bautista quadrangles, lenses of white limestone seem to be interbedded with graywacke rather than with volcanic rocks.

Origin. The origin of the various kinds of limestone in the assemblage of Franciscan rocks can be ascribed to several different, but probably related, processes.

Table 11. Analyses of Calera type of Franciscan limestone.

	1	2	3	4	5	6
SiO_2	2.08	1.52	1.56	17.2	0.91	0.08
Al_2O_3	0.56	0.47	0.47	1.4	0.61	Nil
Fe_2O_3			0.22	0.6	0.30	0.07
MgO	0.20	0.14	0.21	0.3	0.77	0.34
CaO	54.44	54.84	54.43	44.2	55.11	53.8
CO_2	42.92	43.33	42.99	(34.7)	42.24	44.7
Total	100.25[a]	100.45[b]	99.99[c]	98.4	100.36[d]	99.87[e]
$CaCO_3$	97.36	98.17	97.42	78.9	97.35	98.5

1-2. Limestone from Permanente Canyon, Palo Alto quadrangle, Santa Clara County, California. (Lawson, 1919, p. 5). Analysis by W. L. Lawson.
3. Limestone from Black Mountain, Palo Alto quadrangle, Santa Clara County, California. (Huguenin and Costello, 1921, p. 185). Analysis by S. A. Tibbetts; recast.
4. Average of 8 analyses of bulk limestone from Permanente Quarry, Palo Alto quadrangle, Santa Clara County, California. Data supplied by Permanente Cement Co.; analyst unknown. CO_2 calculated.
5. Oölitic limestone from Longwall Canyon, Los Gatos quadrangle, Santa Clara County, California. Analysis by A. C. Vlisidis, U.S. Geol. Survey.
6. Oölitic sand from Dollar Harbor, South Cat Cay, Bahama Islands (Newell, Purdy, and Imbrie, 1960, p. 489). Analysis by Arthur Horen.
[a] Includes 0.05 H_2O and trace of SO_3 and P_2O_5.
[b] Includes trace of SO_3 and P_2O_5.
[c] Includes 0.05 Mn_2O_3, 0.15 H_2O, and 0.06 P_2O_5.
[d] Includes 0.01 MnO, 0.10 H_2O, and 0.31 P_2O_5.
[e] Includes 0.34 NaO(?), 0.04 K, 0.19 NaCl(?), and 0.30 SO_4. CO_2 reported as "loss on ignition" and probably includes some H_2O.

Some small deposits, such as the organic detrital, pelletal limestones, were formed mainly by mechanical abrasion of shell material; and others, such as the oölitic limestone in the New Almaden area, were formed by chemical precipitation in shallow, agitated waters. For the bulk of the Franciscan limestone, however, an origin different from either of the two mentioned seems to be required.

Table 11a. Analyses of Laytonville type of Franciscan limestone.

	1	2
SiO_2	2.0	2.4
Al_2O_3	0.61	0.42
Fe_2O_3	2.3	2.6
FeO	0.23	0.00
MgO	0.00	0.00
CaO	52.8	50.0
Na_2O	0.10	0.14
K_2O	0.08	0.08
H_2O^-	0.32	0.34
H_2O^+	0.66	0.65
TiO_2	0.02	0.02
P_2O_5	0.12	0.12
MnO	0.48	0.59
CO_2	40.7	41.5
Total	100	99.
$CaCO_3$	92.5	89.3
Powder density	2.73	2.74

1. Red limestone (62-1). From crest of Smith Ridge, 6,900 feet N. 36°W. of Black Mountain, Fort Ross 7½-minute quadrangle, Skaggs quadrangle, Sonoma County, Calif.
2. Red foraminiferal limestone (62-26). North Branch Road, 3,000 feet S. 25° W. of Rockpile Peak, Ornbaun SE 7½-minute quadrangle, Ornbaun quadrangle, Mendocino County, California.
Samples analyzed by methods described in U.S. Geol. Survey Bull. 1144-A. Analyses by Paul Elmore, S. D. Botts, Gillison Chloe, Lowell Artis, H. Smith.

The presence of appreciable amounts of pelagic foraminiferal tests in the Franciscan limestone at first suggests an analogy with Recent deep-sea *Globigerina* ooze deposits, but other features seem to contradict this. Today, *Globigerina* oozes are forming in warmer parts of oceans above a critical depth wherever deposition of terrigenous material is scant, and much is known concerning their chemistry and rate of deposition. According to Kuenen (1950, p. 352) the amount of lime in such *Globigerina* oozes ranges from 30 to well over 90 percent, with the average being about 65 percent. The higher values, which are those that approach the values of Franciscan limestones most closely, are reported from oozes obtained from depths of 1,000 meters or less, and the lower values are reported from depths of 4,000 to 5,000 meters. Below this latter depth, the amount of lime in sediments decreases abrubtly, owing mainly to dissolution of lime in colder, more highly carbonated water.

The scarcity of terrigenous material in the Franciscan limestone indicates either that the currents responsible for deposition of graywacke and shale were prohibited from reaching sites of limestone deposition, or that limestone deposition was so extremely rapid as to mask the terrigenous increment. Conceivably, deposition of limestone on topographically high areas or on volcanic seamounts could effectively isolate the limestone from contamination; however, Hamilton (1956, p. 34) and others have shown that current activity is sufficient to maintain Recent seamounts as regions of nonaccumulation of *Globigerina* ooze. Possibly, the ooze could be deposited on the seamounts and then be washed, or slumped, into adjoining protected basins where it could accumulate as discontinuous, lens-shaped masses. Although both the organic detrital and oölitic limestones may have been displaced from shallow into deeper water, the more abundant foraminiferal limestones show no evidence of having been winnowed or sorted by current activity, nor have slump structures or other features indicative of mass movement been observed. A lack of mixing together of interbedded limestone and tuffaceous volcanic material also argues against sliding or slumping. Average rates of deposition of *Globigerina* ooze in the Atlantic and Indian Oceans were determined by Schott (1939) as 1.2 and 0.6 cm per 1,000 years. At an average depositional rate of 1.0 cm per 1,000 years, the age span of the thickest of the bodies of the Calera-type limestone would be about 20 million years, or equal to about half of the entire Late Cretaceous. Although the age span of the Franciscan limestone is not known precisely, no clear-cut paleontologic sequence or age differentiation has been established, even within limestone masses that are hundreds of feet thick. This suggests that deposition was quite rapid and probably exceeded the present rate of accumulation of ooze.

These differences between Franciscan limestone deposits and Recent *Globigerina* ooze deposits are sufficient to suggest that the Franciscan limestone may have had a different mode of origin. Judging from its extremely fine grain size, its sporadic distribution in lens-shaped pods, its nearly constant association with volcanic rocks, as well as the variable abundance and seemingly random distribution of Foraminifera, the typical Franciscan limestone may have been a result of volcänic activity and formed by direct chemical precipitation of calcite with concomitant accumulation of minor amounts of organic shell material, mainly foraminiferal tests. A similar association of submarine volcanic rocks, red limestone, and chert, lithologically comparable to the Franciscan, has been described by Park (1945) from the Olympic Mountains, Washington. Park, drawing on earlier work of Kania (1929), suggested that submarine extrusion of lava together with fumarolic activity caused the precipitation of $CaCO_3$ through the release of CO_2 by agitation and warming of the sea water. Lime may have been made available by the reaction of sea water and erupting magma, as chemical analyses of pillow lavas and tuffs (see tables 4-7) suggest that mafic Franciscan magmas lost large amounts of lime to the ocean. The abundant ferruginous material in the red limestone may also have resulted from the reaction of sea water and lava and the coprecipitation of ferric hydroxide. Its similarity to the coloring matter in the red Franciscan cherts and shales, as well as local occurrences of red limestone and chert together, suggests a common origin of the ferruginous material in both limestone and chert. The absence of ferruginous material in the light-colored limestone of the Calera type indicates a somewhat different environment, perhaps due to a difference in depth of deposition in which iron either was not extracted from the magma or remained in solution in the sea water as a ferrous compound. It may be significant that all of the limestones that afford some textural or faunal indication of shallow-water origin are associated with the relatively iron free Calera type.

In summary, the bulk of Franciscan limestones appears to be chemical precipitate genetically associated with volcanism. Differences in the environment of deposition led to either the formation of a light-colored, iron-free, Calera type of limestone, or to the red iron-rich, Laytonville type. The depth of water in which the limestone was deposited is not known with assurance, but the dominance of open-ocean, pelagic Foraminifera, and the scarcity of a shallow-water benthonic mega- and micro-fauna, suggests fairly deep water, perhaps bathyal, for the majority of the deposits. However, other kinds of limestone, which occur in small amounts, are nonferruginous oölitic limestone and organic detrital limestone. Both of these clearly originated in shallow water, perhaps in the vicinity of seamounts or islands, but their present restricted distribution in small pods, and their association with supposed deeper water, foraminiferal varieties, suggest redeposition in deeper water through the action of submarine slides or turbidity currents.

ULTRAMAFIC ROCKS

Ultramafic rocks, chiefly serpentinites, comprise a significant part of the Franciscan terrane and are of considerable economic interest, because they contain all of the chromite, magnesite, and asbestos deposits and many of the highly productive mercury deposits of the Coast Ranges. Tests made in Russia (Asinkritov, 1956) suggest all the ultramafic rock, except the most sheared serpentinite, should be suitable for road metal for "cold-asphalt" roads. In addition, because of their unusual physical properties, the more serpentinized varieties are of special concern to engineering geologists dealing with problems of highway or dam construction. The ultramafic rocks are generally excluded from the Franciscan when it is treated as a formation, because these rocks intrude the Franciscan sedimentary and volcanic rocks. They are, however, an integral part of the eugeosynclinal assemblage, as are ultramafic rocks in similar assemblages in other parts of the world, and therefore no discussion of the eugeosynclinal assemblage that omits the ultramafic rocks could be considered to be complete.

The ultramafic rocks are widely distributed throughout the entire expanse of the Franciscan, and although most areas comprising several hundred square miles of Franciscan rocks will be found to contain at least some ultramafic masses, the masses are generally largest and most abundant along or near contacts between the Franciscan and the Great Valley sequence (pl. 1). Ultramafic masses are of equal or greater abundance in the Paleozoic and older Mesozoic rocks of the Klamath Mountains and western Sierra Nevada provinces, but, curiously, the metamorphic and granitic terrane in the southern Coast Ranges between the San Andreas and Nacimiento faults is nearly devoid of ultramafic rocks (Fiedler, 1944).

The Franciscan ultramafic rocks are all intrusive, in contrast to the mafic Franciscan greenstones, which are predominantly extrusive. The ultramafics occur as dikes, as sills, and less commonly, as plugs. These terms, however, are not wholly satisfactory for, as will be subsequently discussed in greater detail, many of the serpentinized masses appear to have been emplaced as serpentine rather than as a fluid magma or even a crystal mush, and their margins are therefore faults rather than normal igneous contacts.

Megascopic features. The largest ultramafic body in the Coast Ranges is the sill-like mass that throughout much of its length separates the assemblage of Franciscan rocks of the northern Coast Ranges from the Great Valley sequence exposed along the west side of the Sacramento Valley. This mass varies in width from less than a mile to 5 miles and is exposed over a length of nearly 70 miles. Other sill-like masses

Photo 45. Exposure of partly serpentinized peridotite and dunite in the pluglike Cazadero ultramafic mass, Skaggs quadrangle.

have roughly similar outcrop proportions but range in size down to mere pods only a foot or less in width. Of rarer occurrence are pluglike masses that are a few miles in maximum diameter and roughly elliptical in horizontal section. Some of these, like the Burro Mountain (Cape San Martin quadrangle), Del Puerto (Mount Boardman quadrangle), Red Mountain (Leggett quadrangle), and Cazadero (Skaggs quadrangle) masses contain large amounts of unserpentinized peridotite and dunite, but the still larger New Idria plug consists of wholly serpentinized, and generally sheared, ultramafic rock (Eckel and Myers, 1946, p. 89).

The field appearance of the ultramafic rocks depends on their composition, degree of serpentinization, abundance of shears, and size, and on local climatic factors; still the larger masses can nearly always be recognized even from a distance. The surface expression of the typical serpentinized tabular mass of moderate size in the Coast Ranges is a boulder-strewn slope on which the vegetation is different, and generally less dense, than in the adjacent area. In many places the boulders and accompanying soil have reddish hues owing to oxidation of the iron minerals in the serpentine, but in some areas greenish or gray-green hues predominate. From a distance the slopes may display a crude banding that is a result of a variation in the size or quantity of the boulders. Closer inspection of good exposures or roadcuts reveals that the typical serpentinite mass consists of two different components—blocks and matrix. The blocks, which may range in size up to 10 or more feet but are generally smaller, consist of virtually completely serpentinized peridotite in which the original texture is well preserved. Pyroxene crystals are replaced by a serpentine

Photo 46 (left). Typical exposure of blocky serpentinite. Smooth slopes at right underlain by graywacke. Tiburon Peninsulo, Marin County. (*Photo by Salem Rice.*)

Photo 47 (right). Blocky outcrop of serpentinite derived from peridotite showing choracteristic texture developed on weothered surfoces. Tiburon Peninsula, Morin County. (*Photo by Solem Rice*).

Photo 48. Bare surface developed on highly sheared serpentinite in the New Idria diapiric intrusion. New Idria quadrangle.

mineral forming "bastite," and these generally resemble phenocrysts set in a "groundmass" of serpentinized olivine. Owing to differential weathering, in outcrops the bastites generally protrude above the general surface of a boulder giving it a rough appearance. The shapes of the larger blocks tend to be rectangular with rounded corners, whereas the smaller ones are generally much rounder. Between the blocks is a highly sheared, nearly schistose, serpentinite sometimes referred to as slickentite. The proportion of "matrix" to blocks is quite variable, there being generally less matrix where the blocks are largest, and a gradation toward a marginal zone that is largely slickentite with only small, scattered, rounded boulders. Of course, there are many departures from this generalized description, as some serpentinite masses are little sheared and do not show this blocky aspect, and others consist entirely of sheared serpentinite in which no relict textures can be distinguished. Smaller masses that are completely serpentinized and intensely sheared are not resistant and are normally not well exposed. Such masses cannot be closely delineated in geologic mapping, but many that underlie swales can be recognized by a mantle of distinctive dark-gray or black soil that contracts markedly on drying.

The less common masses that are only partly serpentinized are also little sheared, and they present a different appearance. Where they are deeply dissected, as in the Cazadero or Del Puerto masses, they form picturesque craggy steep slopes or cliffs generally of a red, reddish-orange, or red-brown color. On these slopes vegetation is sparse and exposures may be nearly continuous over wide areas. Most of these masses have well-developed joint systems, with joints spaced at

few-inch to several-feet intervals. These joints tend to control the weathering and the paths of the drainageways down the steep slopes. In a few places on the canyon walls, one can discern layering resulting from an alteration of olivine- and pyroxene-rich layers; more commonly one sees an irregular pattern of craggy and smooth surfaces resulting from irregular distribution of fresh and serpentinized rock. Flat or rolling upland surfaces that remain from an earlier cycle of erosion are found on some of the ultramafic masses, and parts of these surfaces are mantled by a deep, brownish-red, lateritic soil, which may locally contain sufficient nickel to be of commercial value.

The effect of the ultramafic rocks, and the soils derived from them, on the vegetation is so marked that many geologists have called attention to it. These effects vary greatly with the local climate. For example, in the most northern Coast Ranges digger pine grows chiefly on serpentinite, and azaleas also flourish in serpentine soil. In parts of the drier southern Coast Ranges manzanita forms a dense thicket on serpentinite but is sparse on the other rocks in the same area. The Cazadero mass, which is only partly serpentinized, underlies an area known as The Cedars as it supports a dense growth consisting chiefly of Sargent cypress, incorrectly referred to as cedar, and this growth is quite unlike the surrounding vegetation of oak-studded grasslands and redwood-fir forests. The vegetative selectivity observed on both fresh and serpentinized masses seems obviously to be due to the inability of the soil to support most plants, but whether the unusual character of the soil is due to an excess or a deficiency of certain elements has not been determined. In view of a widespread utilization of serpentinite soil as topsoil for home lawns and gardens, for which the only thing to recommend it is its deep-black color, more should be learned of its chemical, and perhaps its physical, deficiencies.

Included under the term "ultramafic rock" are several related rocks that are generally given different names depending on the relative proportions of a few primary magnesium-iron silicates, chiefly olivine and pyroxenes, plus these same two rocks in various degrees of serpentinization. Where these rocks are both completely serpentinized and sheared, the parent ultramafic rock cannot be precisely determined, and such rocks can be classed only as serpentinites. Where the rocks are wholly serpentinized but are unsheared, the original textures are largely preserved. As the serpentinization process is one of replacement by pseudomorphism, the relative proportions of replaced olivine and pyroxene may readily be determined, and in such cases the rocks may be referred to as serpentinized dunite or serpentinized peridotite. Many of the other names applied to varieties of ultramafic rocks are based on the presence or abundance of orthorhombic and monoclinic pyroxenes. However, if the variety of pyroxene cannot be determined, a more precise name for the serpentinized rock cannot be applied. Some of the Coast Range ultramafic rocks must, therefore, be classed only as serpentinite, but most of the larger serpentinized masses contain at least some unsheared material, thus permitting one to determine if the parent rock was dunite or peridotite. On this basis of determination it is clear that a large part, probably over 90 percent, of the Coast Range serpentinites were originally peridotite, but the fresh ultramafic rocks that have been studied in greatest detail have come from the pluglike masses which contain a much higher proportion of dunite.

Dunite, which contains olivine and less than 5 percent pyroxene, though comparatively rare in either fresh or serpentinized condition, occurs in completely fresh condition in the central parts of the Cazadero, Burro Mountain, Red Mountain (Mendocino Co.), and Del Puerto masses. Serpentinized dunite also occurs in some of the thicker tabular masses, but little is known of the distribution of the dunite within them. Peridotite, containing more than 5 percent pyroxene as well as olivine, is by far the most common parent rock for the Coast Range serpentines, but, except where in pluglike masses, it is generally completely serpentinized. The quantity of pyroxene in the unaltered peridotite reported in the literature ranges from 10 to 50 percent, but in many masses it amounts to about 20 percent and is rather uniformly distributed. Varietal names like harzburgite, saxonite, lherzolite, and wehrlite can be applied to different types of peridotite if the pyroxenes have not been entirely serpentinized, but the unserpentinized rocks are rare. The available data indicates harzburgite (saxonite), with orthorhombic pyroxene, is considerably more abundant than varieties with a clinopyroxene. Pyroxenite, consisting almost entirely of enstatite or diallage, and frequently coarsely crystalline, is more resistant to serpentinization than is ultramafic rock containing olivine. Pyroxenite is found in a fresh condition in small amounts in the pluglike masses, in places as late veins along joints, and locally in some of the more serpentinized sills.

Microscopic features. Although parts of several ultramafic masses were mapped in considerable detail by the Geological Survey during World War II investigations of chromite deposits, none has been intensively studied petrographically. Thin sections of fresh dunite show a granular aggregate of anhedral crystals of olivine from 2 to 3 mm in size and accompanying anhedral to euhedral grains of chromite or picotite a little less than 1 mm in size. Sections of peridotite reveal pyroxene crystals a little larger than the olivine crystals and with better developed crystal outlines. In some peridotites the pyroxene encloses grains of olivine. Where the rocks have been strained, the olivines may be highly twinned and locally crushed, and the pyroxenes may show deformation by bent alternating lamellae of orthopyroxene and clinopyrox-

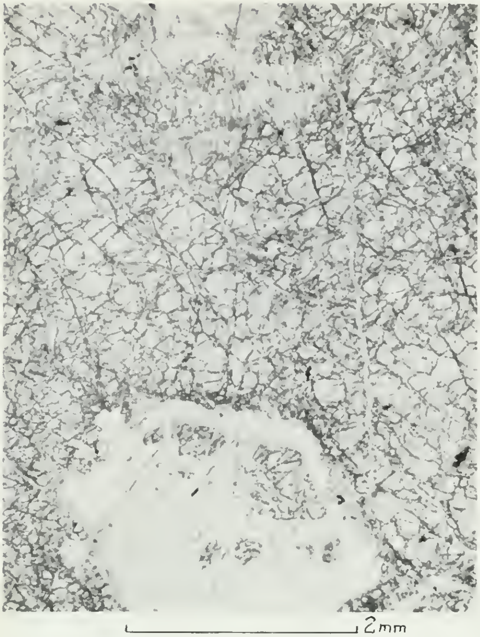


Photo 49 (above). Slightly serpentinized peridotite. Large light area is crystal of pyroxene largely altered to antigorite. Light gray areas near top of photograph are unserpentinized clinopyroxene. Most of the rest is olivine cut by narrow veinlets of antigorite and minor chrysotile. Black grains are chromite. Cazadero mass, Skaggs quadrangle (62-106).

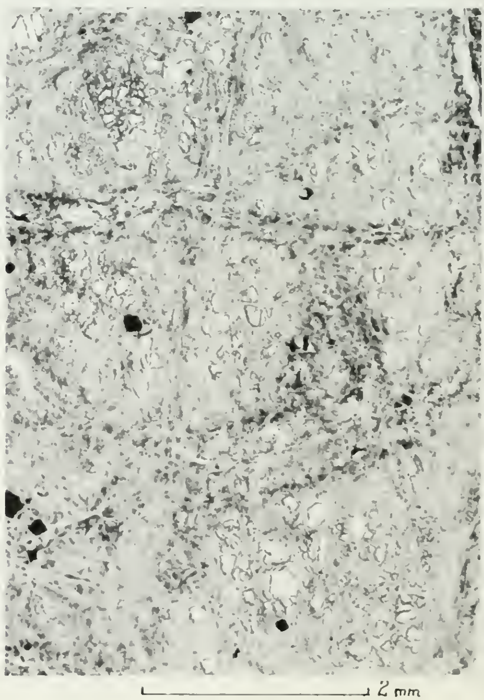
ene. The olivine in dunite in the Del Puerto area is reported to average $Fo_{90}Fa_{10}$ by Maddock (1955), and the olivine in related peridotite he determined as $Fo_{85}Fa_{15}$. Bell (1939) reported that the olivine of the peridotite at Burro Mountain ranged from $Fo_{82}Fa_{18}$ to $Fo_{72}Fa_{28}$. Pyroxene in the peridotite of the Del Puerto area averaged $En_{82}Fs_{18}$, and in pyroxenite ranged from $En_{78}Fs_{22}$ to $En_{87}Fs_{13}$ (Maddock, 1955); at Burro Mountain the range reported by Bell (1939) was $En_{88}Fs_{12}$ to $En_{85}Fs_{15}$. The ranges in chemical composition of chromite from the ultramafic rocks have been determined repeatedly because the selling price of chromite ore is determined by both the Cr_2O_3 content of the ore and the Cr:Fe ratio of the chromite. For the southern Coast Ranges, Walker and Griggs (1953, p. 50) list the Cr:Fe ratio of 2.8:1 for lump ore and 2.73:1–2.18:1 for disseminated ore. For the northern Coast Ranges, Dow and Thayer (1946) give ranges of 3.2:1–2.5:1.

Thin sections of unsheared serpentinized ultramafic rock clearly show the texture of the parent rock, as olivine yields the familiar mesh-structure serpentine and pyroxenes generally are replaced by "bastite." As the pyroxene is more resistant to serpentinization than is the olivine, in some specimens the pyroxenes remain fresh while the olivine is largely converted to serpentine minerals. The change from olivine to serpentine releases iron, which first forms a magnetite dust along the major strands of the mesh structure, and then in a more advanced stage is collected to form larger magnetite crystals or coatings on the primary chromite crystals.

The most common variety of serpentinite, however, is pervasively sheared, and thin sections of it show only sheared lentils of randomly arranged serpentine minerals that reveal nothing about the texture or mineral proportions in the parent rock. Another kind of serpentinite, which also in section shows nothing about the texture of its parent rock, is composed of interlocking tablets of true antigorite. This kind, which is harder and tougher than most serpentinite, is really a metaserpentine formed by recrystallization of one of the kinds of serpentinite described above, and it generally occurs in areas that also contain other kinds of metamorphic rocks.

Gabbro, diorite, and associated coarse diabase have been found in a few areas in the Coast Ranges, but

Photo 50 (below). Incompletely serpentinized dunite showing some unaltered cores of olivine in a meshwork of antigorite. Black areas are crystals of chromite. Shadowy grey areas contain a brownish serpentine mineral sometimes referred to as bowlingite. Cazadero mass, Skaggs quadrangle (62-111).



the volume of these rocks as compared to either serpentinite or the greenstone is very small. No one has made a special study of these rocks, and it is not yet clear whether they are more closely related to the ultramafic intrusive rocks or the dominantly extrusive greenstones, or whether they represent an intermediate magmatic type.

Hornblende quartz gabbro is reported to occur as a sill 1,300 feet thick in the Ortigalita Peak quadrangle (Briggs, 1953a, p. 17-18), and a similar rock forms a plug nearly a mile in diameter in the Tesla quadrangle (Huey, 1948, p. 20-21). In the Mount Hamilton quadrangle Crittenden (1951, p. 21-23) noted segregations of hornblende diorite and gabbro in serpentinite, and a small intrusion of hornblende gabbro into the Franciscan rocks. Near Harbin Springs in the Lower Lake quadrangle Brice (1953, p. 16) mapped a sill of diabase-gabbro with coarse-grained pegmatitic phases intruded between serpentinite and Knoxville shales, and 4 miles to the south Bailey (1946, p. 208) delineated a hornblende diorite-gabbro mass intruded between serpentinite and greenstone. In the northwest corner of the Healdsburg quadrangle a differentiated sill 2,000 feet thick composed of peridotite, gabbro, and diabase has been studied by Gealey (1951, p. 15).

Where the relations between these rocks and Franciscan sedimentary and volcanic rocks are clear, the gabbro-diorite masses are intrusive into the Franciscan, but their absence from the younger rocks of the Coast Ranges, as well as the incipient development of blue amphiboles reported in several of them, indicates they are properly regarded as a part of the Franciscan eugeosynclinal assemblage. Locally the gabbro and pegmatitic gabbro are intimately mixed with serpentinite and seem more to be calcic differentiates of the ultramafic magmas. A further study of these unusual rocks, particularly a study of their chemistry, can be expected to establish if they are genetically related to the greenstones, and it may indicate whether or not the magma that formed the greenstone had the same ultimate source as the ultramafic magma or arose from an entirely different level in the earth's crust.

Chemical features. Chemical analyses of unserpentinized ultramafic rocks from the Coast Ranges are given in table 12, and analyses of serpentinized varieties are shown in table 13. The distribution of the sample localities is shown on figure 17. With so few analyses of these unusually variable rocks, it is not possible to discern any significant chemical differences between them and typical ultramafic rocks of the alpine-type found in other parts of the world. The close correspondence of the serpentinites to the alpine-type of ultramafic rock is also indicated by the Cr:Fe ratio with contained chromite being greater than 2.0:1 (Thayer, 1960, p. 255). If the analyses of the unaltered and serpentinized varieties are compared, the only systematic difference between them is simple hydration.

Origin. Most of the ultramafic masses are tabular, and most trend northwesterly with the structural grain of the Coast Ranges and dip steeply in the direction of the prevailing local dip of the enclosing Franciscan rocks. In this respect they are sill-like, even though most of the larger masses have contacts that locally transgress beds. Whether or not they are initially intruded as flat-lying sills and subsequently folded with the sediments, or were intruded after the sediments were upended, is a difficult problem to solve, but it is of considerable importance insofar as the geologic history of the Coast Ranges is concerned. What assumptions are made is critical when one attempts to draw geologic sections across parts of the Coast Ranges because the ultramafic masses can be used as "key beds" in reconstructing folds if these masses were intruded prior to the folding, as is often assumed. On the other hand, if they were intruded along planes of weakness between upended beds, or along steep faults that strike nearly parallel to upturned beds, one must make an entirely different structural interpretation.

Figure 17. Location of analyzed ultramafic rocks listed in table 12, and serpentinites listed in table 13.

Table 12. Analyses and molecular norms of ultramafic and related rocks.

[Analyses 1, 3, 6, 9, and 10 by rapid rock analysis method described in U.S. Geol. Survey Bull. 1036-C. Analyses by P. L. D. Elmore, I. H. Barlow, S. D. Botts, and Gillison Chloe]

	1	2	3	4	5	6	7	8	9	10
SiO_2	43.1	42.75	41.3	43.6	53.25	49.4	56.98	42.76	44.0	45.7
TiO_2	0.01	tr	0.08	0.02	--	0.15	nil	0.17	1.6	0.08
Al_2O_3	0.56	0.35	3.4	1.2	2.80	2.1	1.73	5.71	16.1	17.5
Fe_2O_3	1.2	1.72	5.9	0.70	0.69	2.2	4.04	3.16	1.1	0.2
FeO	6.5	7.03	5.7	7.7	5.93	4.2	4.18	3.30	8.6	3.3
MnO	0.14	0.10	0.19	0.14	0.09	0.14	--	--	0.16	0.08
MgO	45.1	45.40	28.9	45.0	19.91	21.6	27.40	27.11	7.3	11.4
CaO	0.21	0.037	6.4	0.94	16.22	16.9	3.26	10.03	15.9	15.7
Na_2O	0.03	tr	0.13	0.10	0.19	0.16	0.59	2.24	0.97	0.80
K_2O	0.01	nil	0.01	0.06	tr	0.02	0.35	0.49	0.20	0.96
H_2O+	3.2	1.60	7.8	0.88	0.24	3.2	2.04	4.85	3.9	4.4
H_2O-		0.09		0.06	0.05					
CO_2	0.27	0.74	0.13	--	--	0.11	--	--	0.10	0.06
P_2O_5	0.04	--	0.05	0.04	--	0.04	--	--	0.20	0.02
Cr_2O_3	--	0.28	--	--	0.54	--	0.09	0.22	--	--
NiO	--	0.04	--	--	0.07	--	--	--	--	--
Total	100.4	100.14	100.0	100.0	99.98	100.2	100.66	100.04	100.1	100.2

MOLECULAR NORM-CATANORM

	1	2	3	4	5	6	7	8	9	10
Q	--	--	--	--	--	--	5.2	--	--	--
or	--	--	--	--	--	1.0	2.0	3.0	1.0	5.5
plag	--	--	10.0	3.3	8.5	6.0	6.0	23.5	50.2	49.5
C	0.6	0.4	--	--	--	--	--	--	--	--
di	--	--	18.0	0.8	58.0	63.2	11.6	35.6	32.0	30.0
hy	24.0	21.0	27.4	16.4	30.6	13.0	71.2	--	1.6	--
ol	73.8	74.4	37.5	78.6	2.4	14.7	--	43.3	10.8	16.6
mt	1.2	1.6	6.3	0.6	0.7	2.4	4.1	3.3	1.2	0.3
hm	--	--	--	--	--	--	--	--	--	--
il	--	--	0.3	--	--	0.2	--	0.2	2.4	0.2
ap	--	--	--	--	--	--	--	--	0.5	--
cc	0.4	0.8	0.4	--	--	--	--	--	0.2	--
$MgCO_3$	0.2	1.0	--	--	--	--	--	--	--	--
Silica deficiency	--	--	--	--	--	--	--	(—8.7)	--	(—1.9)
Mg/Fe in silicates	13.5	12.9	18.6	10.9	6.3	13.0	21.5	28.0	2.0	6.4

1. Peridotite (58-363), near Layton chrome mine, Fort Ross quadrangle, Sonoma County, Calif.
2. Peridotite, Red Mountain, Santa Clara County, Calif. (Bodenlos, 1950, p. 233). Analysis by Charles Milton.
3. Peridotite (59-347), from banded intrusive, in canyon 10,200 ft N. 56° W. of Bummer Peak, Skaggs Springs quadrangle, Sonoma County, Calif.
4. Peridotite (62-34), Red Mountain, Leggett quadrangle, Mendocino County, Calif. Analysis by P. L. D. Elmore, S. D. Botts, Gillison Chloe, Lowell Artis, and H. Smith. Powder density, 3.26.
5. "Fresh pyroxenite with some olivine" east of Bagley Creek, Mount Diablo, Contra Costa County, Calif. (Turner, 1891, p. 406) Analysis by W. H. Melville.
6. Pyroxenite (59-349), same locality as no. 3.
7. Enstatite pyroxenite, near Coyote Station, Santa Clara County, Calif. (Kramm, 1910, p. 334). Analysis by H. E. Kramm.
8. "Pyroxenite-peridotite," Oakhill area, Santa Clara County, Calif. (Kramm, 1910, p. 334). Analysis by H. E. Kramm.
9. Gabbro (59-410), Quicksilver Flat, northwest quarter of the Tombs Creek quadrangle, Sonoma County, Calif.
10. Gabbro (59-348), same locality as no. 3.

Evidence regarding the time of the intrusion of the sill-like masses relative to the development of the enclosing structures may be sought in: (1) the internal layering due to crystal settling, (2) the symmetry of a metamorphic aureole, if any, (3) the shapes of the masses relative to the structures in the enclosing rocks, and (4) the coincidence of the ultramafic masses with known faults.

Parallelism of internal layering due to crystal settling in an igneous mass with the attitude of enclosing beds provides good evidence for the intrusion of magma as a flat-lying sill. This criterion has, however, not been found to be of any value in interpreting the relations in the Coast Ranges because such layering has generally not been observed in the serpentinized ultramafic masses. Perhaps this parallelism could be applied to the relatively few masses that are known to contain both serpentinized dunite and peridotite if such masses were studied in great detail.

Asymmetric metamorphic aureoles around a tabular intrusive mass suggest intrusion in a horizontal position with consequent greater metamorphism along the upper surface, whereas symmetrical aureoles suggest intrusion of a near-vertical mass. Unfortunately, most of the Coast Range ultramafic masses, like those in other parts of the world, show no contact metamorphism along their margins. An unusual metamorphic zone containing nephrite, diopsidic-jadeite, and idocrase along the margins of serpentinite sills on Leech Lake Mountain, in the Covelo quadrangle, has been described by Chesterman (1960). Apparently the contact effects here are so erratically distributed that no

Table 13. Analyses and molecular norms of serpentinized ultramafic rocks.

	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	37.62	40.50	42.06	41.47	36.57	39.60	39.98	37.36	39.64	41.86	35.98	36.43
TiO_2	tr	--	--	0.04	--	--	tr	0.01	--	--	0.05	0.04
Al_2O_3	1.20	0.78	2.72	1.35	0.95	1.94	1.12	1.42	1.30	0.69	3.19	3.04
Fe_2O_3	8.60	4.01		2.62	7.29	--	13.19	3.69	--	--	6.36	3.68
FeO	2.15	2.04	2.88	5.57	0.37	8.45	1.05	3.65	7.76	4.15	1.72	3.72
MnO	--	0.13	--	0.24	0.10		-	0.09	0.12	0.20	0.09	0.09
MgO	37.59	37.43	39.53	36.03	40.27	36.90	30.49	38.54	37.13	38.63	37.60	36.99
CaO	2.49	0.39	--	nil	0.14	--	0.46	nil	--	--	nil	nil
Na_2O	0.27	0.28	--	nil	0.31	--	0.28	nil	--	--	nil	nil
K_2O	tr	0.16	--	nil	tr	--	0.25	nil	--	--	nil	nil
H_2O+	10.46	10.94	12.04	12.05	12.43	12.91	13.26	13.50	13.81	14.16	14.16	15.00
H_2O-		2.81	--	0.76	0.94	--	--	--				--
CO_2	--	--	--	nil	--	--	--	0.88	--	--	0.84	0.54
Cr_2O_3	0.36	0.41	--	--	0.33	0.20	tr	0.25	0.29	0.24	0.29	0.38
NiO	--	0.11	--	--	0.31	--	--	0.1	0.33	tr	0.2	0.2
Total	100.74	99.99	99.23	100.13	100.01	100.00	100.00	99.5	100.38	99.93	100.5	100.1

MOLECULAR NORM-CATANORM

	1	2	3	4	5	6	7	8	9	10	11	12
or	--	0.8	--	--	--	--	1.5	--	--	--	--	
plag	4.5	3.0	--	--	4.0	--	3.8	--	--	--	--	--
C	--	--	1.5	1.5	--	2.1	-	1.6	1.5	0.8	3.7	3.5
di	8.0	1.2	--	--	--	--	0.8	--	--	--	--	--
hy	15.2	37.8	49.4	48.4	16.4	33.0	57.2	33.4	37.6	44.0	33.2	32.6
ol	64.5	52.5	46.2	47.4	74.1	64.8	25.8	58.8	60.9	55.2	54.9	58.5
mt	5.1	4.5	2.8	2.7	0.9	--	2.7	4.0	--	--	4.2	4.0
hm	2.7	--	--	--	--	--	8.2	--	--	--	1.9	--
$MgCO_3$	--	--	--	--	--	--	--	2.4	--	--	2.2	1.4
Mg/Fe in silicates	∞	541	14.4	14.1	∞	7.8	∞	318	8.6	16.8	∞	29.7

1. Lherzolite serpentine, Sulphur Creek, Colusa County, Calif. (Kramm, 1910, p. 320). Analysis by H. E. Kramm.
2. Serpentine, Bagley Creek, Mount Diablo area, Contra Costa County, Calif. (Turner, 1891, p. 406). Analysis by W. H. Melville.
3. Serpentine, Angel Island, San Francisco, Calif. (Ransome, 1894, p. 231). Analyses by F. L. Ransome.
4. Sheared serpentine, sec. 25, T. 18 S., R. 12 E., near Gem mine, New Idria quadrangle, San Benito County, Calif. (Coleman, 1957, p. 136). Analysis by W. H. Herdsman.
5. Bastitic serpentine. Bagley Creek, Mount Diablo area, Contra Costa County, Calif. (Turner, 1891, p. 406). Analysis by W. H. Melville.
6. Serpentine from Presidio, San Francisco, Calif. (Kramm, 1910, p. 330). Analysis by J. D. Easter.
7. Serpentine, near Missouri mercury mine, Sonoma County, Calif. (Kramm, 1910). Analysis by H. E. Kramm.
8. Sheared serpentine, New Almaden mine, Santa Clara County, Calif. Analysis by F. A. Gonyer, with Al_2O_3, Fe_2O_3, FeO determined by J. J. Fahey.
9. Serpentinized peridotite, near Borax Lake, Lake County, Calif. (Becker, 1888, p. 111). Analyst not given.
10. Serpentine near Borax Lake, Lake County, Calif. (Becker, 1888, p. 111). Analyst not given.
11. Unsheared bastitic serpentine, New Almaden mine, Santa Clara County, Calif. Analysis by F. A. Gonyer.
12. Unsheared bastitic serpentine, New Almaden mine, Santa Clara County, Calif. Analysis by F. A. Gonyer, with Al_2O_3, FeO, and Cr_2O_3 determined by J. J. Fahey.

reliable comparison between their development on upper and lower surfaces of the sills can be made. Glaucophane schists occurring along the margins of sills also have been cited as examples of contact aureoles by several geologists. Taliaferro (1943a, p. 163-165) described a sill on the Tiburon peninsula (San Francisco quadrangle) having extensive development of glaucophane schist above its upper surface and little below it, and he also mentions other localities where similar relations were observed. In the Sebastopol quadrangle, Travis (1952) has mapped a serpentine sill in a plunging syncline with glaucophane schist in the upper or central part and extensive development of schist below. Crittenden (1951) mapped a sill north of Mount Hamilton having glaucophane schist along both margins, but with the greatest amount above the presumed upper surface. As is discussed in the following section that deals with schists, there is considerable doubt that these glaucophane schists formed by contact metamorphism, and in all these localities the schists may be equally well explained as tectonic masses included within or dragged up along the margins of intrusive serpentine masses. Thus, while the glaucophane schists may provide some supporting evidence for a few ultramafic masses having intruded as flat sheets, generally no metamorphic effects are observed, and even where there seems to be contact metamorphism, other interpretations are possible and generally preferable.

The attitudes and shapes of the sill-like masses relative to the structures of the enclosing rocks provide somewhat better data. Where the Franciscan rocks are very steeply inclined, it is generally impossible to trace folds in them, and consequently one cannot tell if associated steeply inclined ultramafic masses were intruded before or after folding. However, in some mapped areas the Franciscan strata are gently folded and enclose equally gently folded sills, doubtless intruded when the beds were nearly horizontal. The sill in the Camp Meeker syncline in the Sebastopol area

is a good example of this kind of occurrence, and a similar sill occurs on the prominence 2 miles east of Mine Hill in the New Almaden quadrangle.

Where the Franciscan beds are steeply inclined, detailed mapping may reveal that the peneconcordant ultramafic masses have an outcrop pattern that differs systematically from the structural pattern in the host rocks. For example, in the western Mayacmas district (Bailey, 1946) the prevailing strike of the folds as reflected by the outcrop pattern is N. 55° W., and superimposed on this and trending N. 25° W. is a structural grain that is due to faults. The elongation of the smaller ultramafic masses and the directions of the margins of the larger masses follow both of these trends, and the ultramafic masses are equally wide along each. These relations indicate the Franciscan rocks were folded, and subsequently intruded by serpentinite along the rhomboid pattern formed by the intersection of the N. 55° W. bedding planes and the N. 25° W. fault planes. Yates (1946) in describing the adjacent eastern Mayacmas district concluded the serpentinite was intruded after the major folding because the ultramafic masses, even though nearly parallel to the beds in strike, consistently dipped more steeply. In other parts of the Coast Ranges the serpentinite masses though locally concordant are straighter in trend and steeper in dip than the bedding of the enclosing rocks, thus indicating that the serpentinite masses were intruded along faults that cut previously folded beds. Locally these faults are parallel to steep bedding planes, but the faults depart from the bedding wherever the beds either dip less steeply or trend more west-northwesterly than the main trend of the faults.

The problem of establishing whether the ultramafic masses are folded sills or intruded along faults becomes much simpler where non-Franciscan rocks form one side of the fault, chiefly because the boundary provides clear evidence of the existence and exact path of the fault. In several places in the Coast Ranges major fault zones contain steep tabular masses of ultramafic rock. The great serpentinite mass separating the Franciscan rocks of the northern Coast Ranges from rocks of the Sacramento Valley has been mentioned. Similar though less extensive masses are found along the Tesla-Ortigalita fault that separates the Franciscan of the Diablo Range from the rocks of the San Joaquin Valley. Other masses of considerable size are found along the southern part of the Hayward fault and the San Andreas fault on the San Francisco peninsula. Such masses may be either intruded along the fault plane at some time later than the youngest rocks bordering the fault, or they may be segments of masses present in the Franciscan prior to the movement of the fault that brought unlike rocks into juxtaposition and thus are older than the adjacent non-Franciscan rocks. Except for the ultramafic masses along the west edge of the Great Valley, the serpentinite along faults bordered only on one side by Franciscan rocks is readily explained by the latter mechanism. The lack of serpentinite along most post-Franciscan faults strengthens this conclusion, and seems somewhat surprising considering the ease with which preexisting serpentinite masses can be remobilized tectonically.

We must conclude, therefore, that some of the ultramafic "sills" were intruded while the Franciscan was little folded; probably most were intruded along faults following the first major folding of the Franciscan rocks, and a few were intruded, or remobilized, along post-Late Cretaceous or younger faults. It is unsafe either to assume that an ultramafic mass was intruded while the Franciscan beds were horizontal, and thus use it as a key bed in reconstructing structure, or to assume it has been intruded along a postfolding fault. However, careful mapping will in many cases supply sufficient data to allow one to interpret the relations of the intrusion to the structure.

The physical condition of the ultramafic masses at the time of their intrusion is as difficult to determine with certainty as is the time of their emplacement. Reasonable speculations regarding their condition might include ultramafic magma, hydrous magma yielding serpentinite by a kind of deuteric alteration, crystal mush, or serpentinite intruded plastically as a so-called "cold intrusion." To treat this problem fully is beyond the scope of this report, and for a more extensive account of the worldwide problem presented by ultramafic rocks, whether serpentinized or not, the reader is referred to a brief, but highly lucid, discussion by Turner and Verhoogen (1960, p. 313-321.) The striking lack of thermal metamorphism along the borders of the masses seems to call for the rejection of direct intrusion of ultramafic magma, which would be completely molten only at the very high temperature of 1,600°C or above. A hydrous magma, according to the experimental studies of Bowen and Tuttle (1949), would, when cooled to a temperature of about 1,000°C, consist of olivine crystals with water in the pore spaces, but at this temperature the water is so tenuous that the quantity held in the pore spaces could on cooling react to form only a minute amount of serpentine. The pluglike Cazadero and Burro Mountain masses contain much nearly fresh dunite, though their borders are highly serpentinized, and it is possible that each of these masses was intruded as a crystal mush, perhaps with the aid of a little hydrous magma serving as a lubricant. The development in the olivine of strain shadows and twinning, as well as mylonitized zones, clearly seen in thin sections, is indicative of this type of intrusion. However, the marked lack of any metamorphism along the margins, as well as the sheared and serpentinized character of the periphery of the plugs, suggests that these masses were emplaced as a crystal mush at a greater depth and have been intruded into their present position diapirically.

The typical tabular ultramafic masses are much more completely serpentinized, and as it seems to be

impossible for them to have been intruded as melts, as hydrous "serpentine magmas," or as crystal mushes, we are forced to conclude that they have been intruded plastically as socalled "cold intrusions." Considerable evidence can be offered in support of this conclusion: (1) lack of metamorphic aureoles, (2) the sheared nature of the masses, (3) the prevalence of shearing in the Franciscan rocks along their contacts, (4) the completeness of serpentinization, and (5) where serpentinization is not quite complete, the lack of localization of the more serpentinized parts along zones that seem most favorable for the migration or collection of water.

The strongest objection to the "cold intrusion" mechanism is perhaps based on the fluidity required for the serpentine to be injected. In some areas where contacts are well exposed, as for example in the New Almaden quicksilver mine, it is possible to see small apophyses diverging from a main serpentinite contact and penetrating the Franciscan sedimentary rocks in a manner that is entirely similar to the small apophyses one finds along the margins of normal magmatic masses in other areas. These sill-like or dikelike apophyses where small are invariably composed of highly sheared serpentinite, and they do not contain the blocks of unsheared material that are typical of the more central parts of the serpentinite masses. Such apophyses clearly indicate that the plasticity of the sheared serpentinite, under the temperatures and pressures existing during its injection, must have closely approached the fluidity of a magma, but these apophyses do not require the material to have been a melt. As is well known to construction and mining engineers, serpentinite even under surface conditions may possess a high degree of plasticity, resulting in landslides that flow on areas of low slope, or in serpentinite pushing into mine workings in spite of heavy timbering. For example, Louderback (1942, p. 309) states, "In the San Pablo Tunnel * * *, the serpentine is so sheared that it flowed under its own weight into the tunnel like a viscous liquid and presented a serious problem of control." Because of this low strength and high plasticity, it is likely that some of the extensive landslides around a few of the larger Coast Range serpentinite masses result from a still-continuing upward flowage of the masses (Bailey, 1942, p. 151).

Alteration of serpentinized ultramafic rocks. The serpentinized masses in the Franciscan terrane of the Coast Ranges have since their emplacement been locally altered to form other kinds of rocks, some of which are of economic importance. The two varieties of chief interest are silica-carbonate rock, which is the host rock for many quicksilver deposits, and magnesite rock, which is used as a source of magnesium and magnesia.

Silica-carbonate Rock

Silica-carbonate rock, or quicksilver rock as it is sometimes termed by miners, is a dense rock formed by the hydrothermal alteration of serpentine. It is widespread in the Coast Ranges with known occurrences extending from near Santa Barbara to at least as far north as Lake Pillsbury. Wherever it is possible to date the time of formation of the silica-carbonate rock, it is late Miocene or younger, so its formation is apparently in no way related to the original process of serpentinization. Its general areal distribution suggests it may be related to mid-Tertiary and younger vulcanism, but some silica-carbonate rock is many miles from known outcrops of volcanic rock. As most of the occurrences are in quicksilver districts, its formation seems to be an early stage of the hydrothermal activity that in later stages deposits cinnabar.

Silica-carbonate rock, as is indicated by its name, consists of one or more silica minerals—chalcedony, opal, or quartz—and a carbonate, which is normally a ferroan magnesite. In many areas the quantity of silica and magnesia in a unit volume of silica-carbonate rock is the same as in a unit of serpentinite, and the mineralogic change is clearly one that results from the direct substitution of CO_2 for the water in the serpentinite. In some areas, notably in the Sulphur Creek and Knoxville mercury districts east of Clear Lake, a more drastic change has taken place resulting in a variety of silica-carbonate rock that is almost all silica, either opal or chalcedony. Ross (1940, p. 333) believes such rocks formerly contained carbonates, which have been replaced by additional silica, and he refers to such masses as "twice-silicified reefs." Locally the opposite relations prevail, and the silica-carbonate rocks are largely carbonate, presumably magnesite. The only other common mineral in these rocks is chromite or picotite, which is unaffected by the changes the rock has undergone. These shiny black crystals can be readily seen with a hand lens, and their presence often is of great help in distinguishing weathered silica-carbonate rock from similar-appearing weathered greenstones.

Where silica-carbonate rocks are developed in abundance they generally form a prominent part of the landscape, because they tend to resist erosion and form conspicuous iron-stained "reefs" or trains of rubble. The rock itself may be very hard and dense, or it may have lost most of its carbonate by weathering and be reduced to a porous network of silica veinlets stained with residual iron oxides.

The silica-carbonate rock everywhere is a replacement of serpentinite, and is most frequently found in the places where hydrothermal solutions are most likely to have had access to the rock, namely along its margins or along throughgoing shear zones. Nearly all silica-carbonate rock has formed from serpentinite that is highly sheared, and it possesses a sheared or microaugen texture, though the rocks show little tendency to break along this relict grain. Rarely silica-carbonate rock forms from serpentinized but unsheared peridotite, in which case the replaced py-

Photo 51. Resistant masses of silico-carbonate rock exposed at the Picocho mercury mine in the New Idria serpentinite mass, New Idria quadrangle.

roxenes can be readily recognized even though they have been through two dissimilar stages of replacement.

As the rock apparently owes its origin to the hydrothermal activity that formed quicksilver ores, it is a useful guide in prospecting for this metal, but not all silica-carbonate rocks contain cinnabar nor are all quicksilver deposits in the Coast Ranges found in silica-carbonate rocks.

Magnesite Rock

Another kind of alteration of serpentinite yielded magnesite rock that has been mined for use in steelmaking, in refractories, and as a source of magnesium and magnesia. The largest and most productive deposits are near the west end of the Del Puerto ultramafic mass in the Red Mountain magnesite district, but about a dozen other deposits in the Coast Ranges have either been prospected or produced in a small way. The production recovered between 1905 and 1945 from the Red Mountain district has been nearly 1,000,000 tons.

The magnesite ore occurs as either replacements of serpentine along shear zones or as massive or recemented breccia veins. Although the commercial deposits are all in serpentinized rock, it is perhaps significant that the Red Mountain deposits and the extensive Red Slide deposits in Sonoma County are in unusually large, possibly diapiric, masses that contain unserpentinized dunite.

The origin of the magnesite deposits is controversial, but probably the conclusions reached by Bodenlos (1950), who made a careful study of the Red Mountain area, apply to all of them. He described the ore as consisting of very fine grained, nearly pure, magnesite which replaced serpentinite along shear zones in less serpentinized dunite and filled fractures in the same zones. The main period of formation of magnesite was followed by minor deposition of chalcedony, opal, deweylite, and perhaps sepiolite. Generally the ores contain a few percent of $CaCO_3$ in the form of dolomite; younger calcite veins cut the ore, and aragonite is deposited from the magnesia-rich waters

flowing from some of the workings. The solutions responsible for the formation of the magnesite are believed by Bodenlos to be carbonate-rich hypogene fluids. They picked up magnesium at some unknown depth and deposited it as they neared the surface and lost some of their carbon dioxide. These solutions are later than those responsible for the serpentinization, though they may have serpentinized the vein walls to a minor degree.

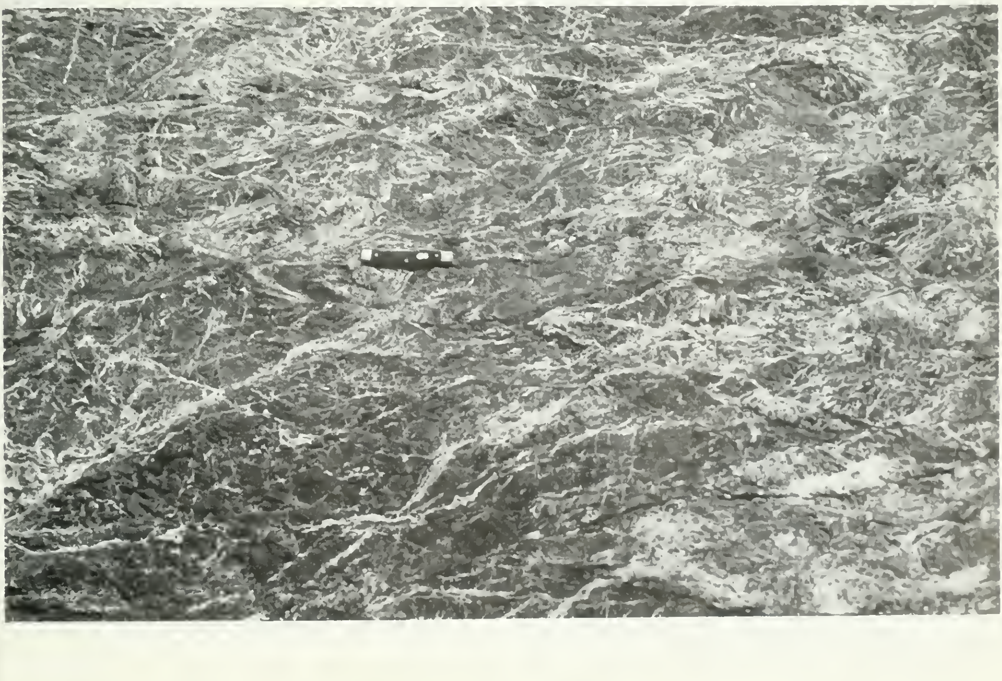
The magnesite deposits cannot be closely dated, but it has been suggested that they are mid-Tertiary or younger in age. The solutions that formed the magnesite ores are therefore both in time and composition much like those that formed silica-carbonate rock, and it is possible that the formation of the magnesite is a near-surface expression of the alteration that at depth forms silica-carbonate rock.

METAMORPHIC ROCKS

The assemblage of Franciscan rocks, though dominantly unmetamorphosed, includes graywacke, shale, greenstone, and chert that are now reconstituted by isochemical metamorphism, and rarer metamorphic rocks formed by metasomatism. The general distribution of the more common varieties is shown on figure 18. The best known are the striking blue glaucophane schists, first noted by Michel-Levy in 1878 when examining mercury ore specimens shipped from California to Paris for an exposition. These blueschists, and related rocks, have been extensively studied because of their rarity and unusual mineralogy, and they are the subject of perhaps as many articles as have been written about all the rest of the assemblage, even though they comprise but a small part of it. Two now widely recognized minerals were first discovered in Franciscan schists—crossite in 1894 (Palache, 1894b), and lawsonite in 1895 (Ransome, 1895). In addition, the first occurrence of aragonite as a metamorphic mineral was found in Franciscan blueschists by Coleman and Lee (1962).

The metamorphic rocks formed chiefly through isochemical recrystallization will be grouped in this report, according to the pressure-temperature environments in which they are believed to have formed, into the following facies: (1) zeolite, (2) blueschists, and (3) eclogite. Rocks assigned to the zeolite facies show metamorphism chiefly by the presence of laumontite. Blueschist facies rocks include those with lawsonite, jadeite, and most glaucophane-bearing rocks. The eclogite facies includes rocks generally referred to as eclogite because they contain omphacitic pyroxene and garnet that is partly pyrope, but it also includes glaucophane-eclogites, glaucophane-epidote rocks, and

Photo 52 (below). Veins of laumontite in greenstone assigned to the zeolite metamorphic facies. On the Wheatfield Fork of the Gualala River in the northwest corner of the Skaggs quadrangle.



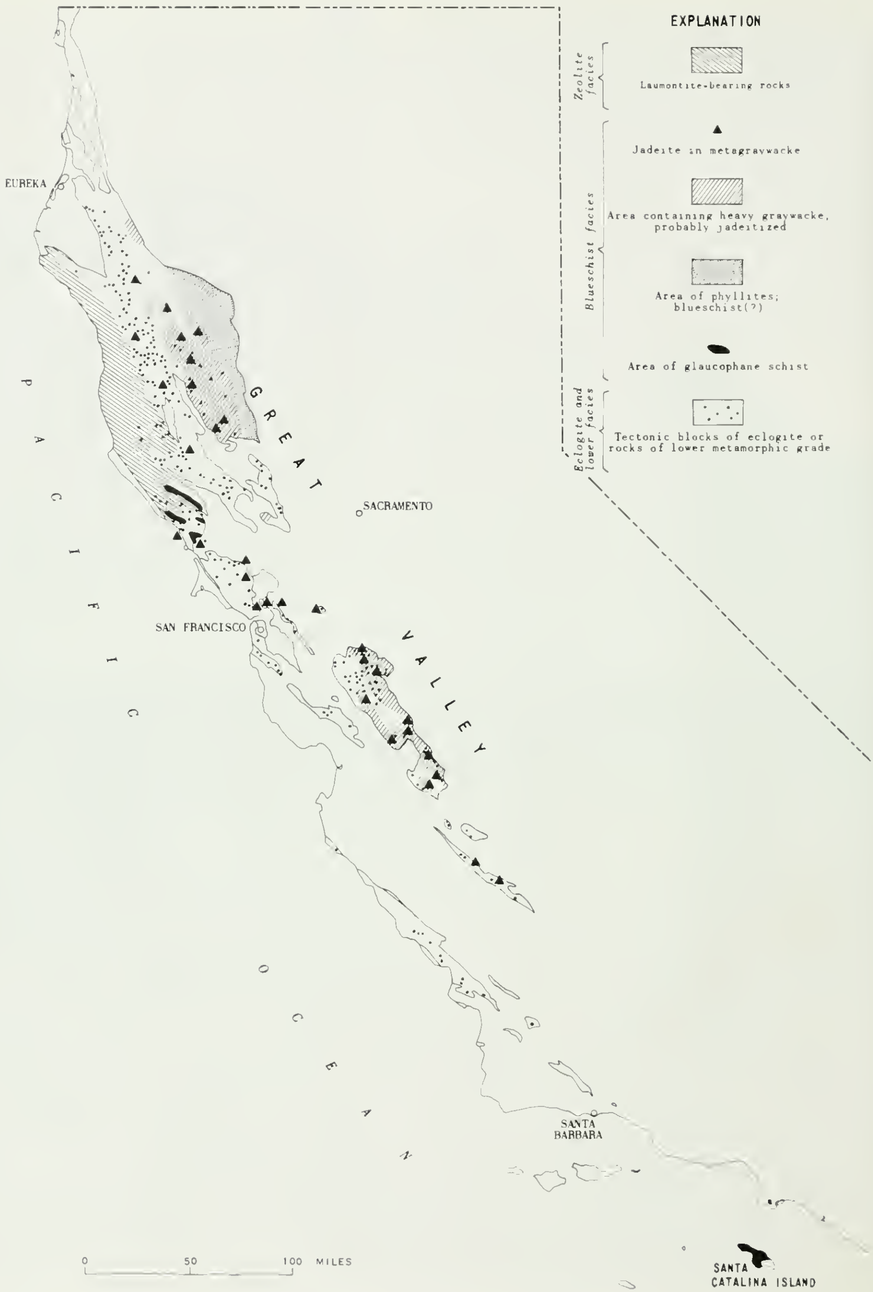


Figure 18. Map showing distribution of metamorphic rocks in the Franciscan.

other rocks with the same unusual occurrence as the eclogite. All of these formed under higher pressure-temperature conditions than the normal blueschists. Although the eclogites differ somewhat from true eclogites, these rocks are included under this facies designation chiefly for the purpose of separating them from the normal blueschists.

The metamorphic rocks involving metasomatism include the tourmalinized graywackes of Mount Tamalpais, Marin County (Rice, 1960), the rodingite inclusions in serpentine, and the more widespread silica-carbonate rocks formed in Tertiary or Quaternary time by the hydrothermal alteration of serpentine. As these have been discussed previously, they are not mentioned further in this section.

Zeolite facies rocks. Laumontite, a calcium-aluminum zeolite, is widely present in the Franciscan rocks in the western part of the northern Coast Ranges. In this area it is most noticeable as a white sugary mineral filling shatter veins in apparently unmetamorphosed graywacke and greenstone, but it also occurs in both rocks as a replacement of plagioclase and as irregular patches in the groundmass of the graywacke. Laumontite from veins has been determined by X-ray, but the determinations of laumontite replacing feldspar are based on the study of thin sections. As Taliaferro (1943a, p. 145) refers to "natrolite and other zeolites" as vesicle fillings in Franciscan greenstone, perhaps a more systematic study of the Franciscan, and especially of the fine-grained material formed by incipient metamorphism, will reveal heulandite or other zeolites. Certainly theoretical considerations indicate zeolitic alteration of the Franciscan ought to be more widespread than is now recognized.

Adularia, though not a zeolite, is included here because of its occurrence in the same metamorphic environment as zeolites. During the examination of graywacke specimens which had been stained to determine their content of K-feldspar, adularia was recognized as a vein mineral in the Franciscan. Its identification as a monoclinic adularia was verified by X-ray technique by R. C. Erd. We have no data on whether or not its distribution is coextensive with laumontite, but it appears to be widespread.

Blueschist facies rocks. The term "blueschist" is used in this report to include the metamorphic rocks of the blueschist facies, which is nearly synonymous with the glaucophane schist facies of Fyfe, Turner, and Verhoogen (1958, p. 12, 173-174). This suggested designation is a term comparable to the more familiar term "greenschist," and it avoids the implication that glaucophane is the only characteristic blue amphibole. The critical mineral for the blueschist facies is lawsonite, but the P-T field of impure jadeite is apparently similar enough so that jadeite can, for all practical purposes, also serve as a critical mineral. Glaucophane, or other soda amphibole, is present in many blueschists, though it is neither entirely restricted to the blueschist facies nor required for the rocks to be assigned to this facies. Stilpnomelane and pumpellyite are common, but these minerals also occur in greenschists. Either aragonite or calcite may be stable with lawsonite in the blueschist facies. A garnet, which is often manganiferous, and sphene are also present in some of these rocks.

The blueschists are the best known metamorphic rocks in the Franciscan and are found throughout its extent. They fall into two natural subdivisions, because under varying conditions the soda in the rock may go to form the sodic pyroxene, jadeite, or may form a sodic amphibole, generally glaucophane. These two sodic minerals are not mutually exclusive, but where they do occur together generally one is much more abundant than the other. We will first discuss jadeitized metagraywacke and follow with a discussion of glaucophane schists.

Jadeitized Metagraywacke

The pure sodium aluminum pyroxene, jadeite ($NaAlSi_2O_6$), according to experimental data (Yoder, 1950) can form in metamorphic rocks only under a combination of such extremely high pressure and moderate temperature that one would not expect it to be a common mineral. However, among the metamorphic rocks of the California Coast Ranges, pyroxenes containing large but variable amounts of the jadeite molecule are abundant in several different environments, and in some the pyroxene is generally referred to as jadeite even though such pyroxene contains only 70 percent of the pure molecule. The first discovery of jadeite in the Franciscan rocks was made by Mielenz (1936) who found jadeite of unspecified composition in a quartz-albite-jadeite-muscovite-glaucophane-lawsonite rock, believed by Taliaferro (1943a, p. 178-179) to be a metamorphosed Franciscan chert. Later massive jadeite of lapidary quality was found in several places in the Coast Ranges as inclusions in serpentine (Yoder and Chesterman, 1951), and some from inclusions in the New Idria serpentine mass was studied by Coleman (1961), who pointed out that this jadeite contains significant amounts of acmite and therefore could form at lower pressures than were experimentally determined for pure end-member jadeite. More widespread, and of greater significance in understanding the metamorphism of the Franciscan, are two other occurrences of sodic pyroxene. In one, omphacite, a pyroxene with 30-50 percent of the jadeite molecule, is a major component of rocks assigned to the eclogite facies. In the other, which will be dealt with at greater length here, a jadeite, containing up to 80 percent of the pure end-member, forms a prominent constituent of Franciscan metagraywacke exposed in several large areas.

Jadeitic metagraywacke was first noted in the Franciscan by Maddock (1955) during a study of the Mount Boardman quadrangle east of Mount Hamilton. Subsequently, similar rocks were described by Bloxam (1956, p. 488-489) as occurring in the Berkeley Hills and on Angel Island in the San Francisco quadrangle,

in the Panoche Valley quadrangle near Glaucophane Ridge, and in the Sebastopol quadrangle near Valley Ford (Bloxam, 1959). Jadeitic metagraywacke has been observed along Tres Pinos Creek in the San Benito quadrangle by W. G. Ernst (written communication, Aug. 3, 1960). Jadeitic metagraywacke occupies an area of many square miles about Pacheco Pass (McKee, 1958a, b; 1962) and has been recorded from the Isabel-Eyler area east of Mount Hamilton, near the top of Mount Diablo, along Miners Road in the Tesla quadrangle, and in the Calaveras Reservoir in the Morgan Hill quadrangle by Soliman (1958). Similar rocks have also been found at Goat Rock in the Duncans Mills quadrangle, on the Tiburon peninsula in the San Francisco quadrangle, and along Arroyo Mocho in the Tesla quadrangle by R. G. Coleman (oral communication, 1960).

Additional data on the distribution of jadeitized graywacke was obtained as a byproduct of a study of the specific gravity of hundreds of graywacke specimens collected from the entire Coast Ranges (see p. 139). To ascertain why some of these normal-appearing graywackes were abnormally heavy, we selected 35 with specific gravities ranging from 2.70 to 2.89, extracted a heavy fraction in bromoform, and X-rayed the heavies. The results of this work, shown on figure 19, indicate the conversion of albite to jadeite is the cause of the high specific gravity and that any Franciscan graywacke with a specific gravity of more than 2.71 probably is jadeitized. Consequently on figure 18 we show areas in which at least some of the graywackes are abnormally heavy as areas containing jadeitized rock. This extrapolation of data, which greatly extends the area believed to contain jadeitized graywacke in the Franciscan, is not substantiated, but by X-ray we found jadeite in selected graywackes from as far north as Zenia in the Kettenpom quadrangle to as far south as Parkfield in the Parkfield quadrangle (see fig. 18).

It is thus apparent that a jadeitic metamorphism of the Franciscan graywacke is widespread, even though it has escaped notice until recently. One large area of its development is in the Diablo Range along a span extending from Panoche Valley northward nearly to Livermore (Livermore quadrangle), a distance of about 75 miles. Another large area, based largely on the occurrence of heavy graywackes, extends for many tens of miles northwestward from Clear Lake. Most of the other more limited occurrences are along the extension of this same belt. It is probably significant that the belt containing jadeitized metagraywacke appears to include the oldest parts of the Franciscan; also noteworthy is the lack of known jadeitized graywacke in the Franciscan west of the Nacimiento fault.

Jadeitic metagraywacke closely resembles normal Franciscan graywacke and usually occurs in unsheared beds showing sedimentary features and no schistosity (photo. 53). It is heavier and tougher than unmetamorphosed graywacke and may possess a greenish-

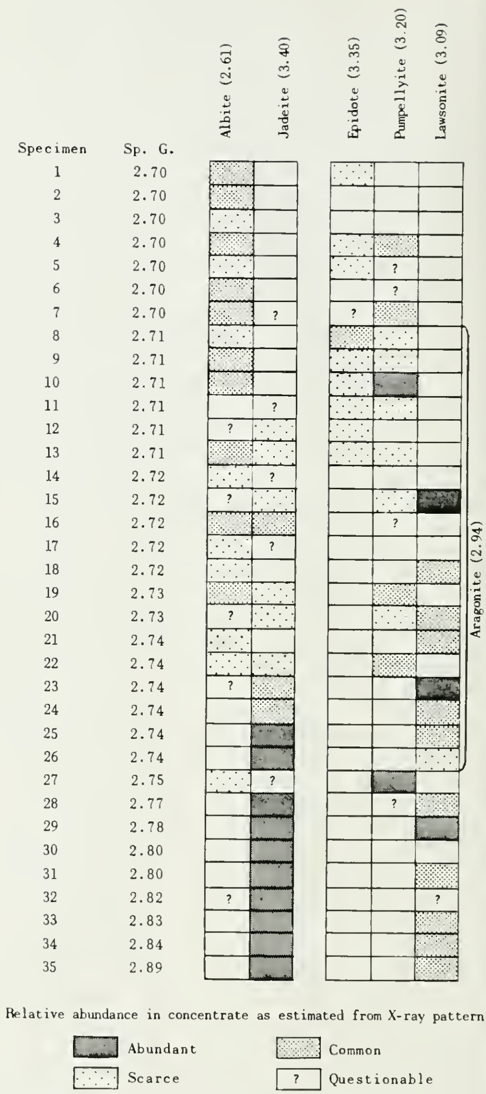


Figure 19. Heavy minerals in heavy Franciscan graywackes.

grey, rather waxy appearance on fresh surfaces. Clastic texture is always visible, but close examination shows that grain boundaries are somewhat less distinct than those in the unaltered rock. Where the jadite is unusually coarse, with the aid of a hand lens it can be seen to form radiating groups or sheaves. In thin section most of the jadeite occurs as small interlocking granules, and the determination of optical properties is difficult except on the larger radial crystals. The most striking optical characteristic of the mineral is its anomalous birefringence, which because of strong dispersion yields colors much like those of clinozoisite. As jadeite forms chiefly from the breakdown of plagioclase, jadeitized metagraywacke in incipient stages generally contains albite, but where the alteration is complete albite is absent. Accompanying metamorphic minerals may include glaucophane, lawsonite, pumpellyite, aragonite, recrystallized quartz, sericite, and chlorite. Although some of the jadeitic rocks are semischists, the retention of the original clastic texture, and the general lack of foliation or schistosity, clearly indicates that stress is not a critical factor in the formation of the jadeitized graywacke.

Glaucophane-bearing Blueschists

Glaucophane-bearing metamorphic rocks are found throughout the extent of the Franciscan, except in parts of the "coastal belt" in the western part of the northern Coast Ranges. They occur in a variety of geologic situations, some of the most peculiar of which have been the most studied yet remain the least understood. These occurrences can, for the purpose of description, be divided into three categories: (1) areas of several tens of square miles in which all of the rocks are regionally metamorphosed; (2) small patches of mildly metamorphosed rocks occurring in an otherwise unmetamorphosed terrain and in places exhibiting gradational relations; and (3) generally rounded blocks, usually tens of feet in diameter but locally much larger, occurring as tectonic inclusions either in the unmetamorphosed parts of the Franciscan or in serpentine. As the tectonic blocks also include eclogite, and glaucophane-eclogite, the discussion of glaucophane rocks occurring in this unusual manner is included later in a section dealing with eclogites.

In the Franciscan are found only a few areas of tens of square miles in extent in which metamorphism has everywhere resulted in the formation of glaucophane-bearing rocks, and it seems likely that in the aggregate such area are less extensive than are areas of jadeitized graywackes. For want of a better term we refer to these few areas as regionally metamorphosed, although they are smaller than areas generally so described. Most of the glaucophane-bearing rocks are schistose and show both foliation and lineation, in contrast to the jadeitized graywackes which are not foliated. The metamorphic minerals in some of the glaucophane-bearing rocks, however, are not oriented, suggesting that directed stress is not required for their formation. Collectively, the glaucophane-bearing rocks are generally referred to, as they are here, as glaucophane schists, even though not all are schistose.

One large area of regionally metamorphosed glaucophane schist comprises the northwest half of Santa Catalina Island (Bailey, 1941), 20 miles offshore from southern California; and a small area of similar rock is exposed in the Palos Verdes Hills on the mainland. However, as has been pointed out by Woodford (1960), these exposures are but a remnant of a much larger area of metamorphic rocks that was exposed offshore from the present mainland in Miocene time. These rocks have been referred to as the Catalina Schist because of the difficulty in establishing a positive correlation with the unmetamorphosed Franciscan Formation of the San Francisco Bay area, but we consider them to be a part of the eugeosynclinal assemblage that includes the Franciscan Formation. On Santa Catalina Island these rocks are now all metamorphosed to some degree, but prior to their metamorphism, they consist of graywacke, shale, conglomerate, mafic volcanic rocks, chert, and serpentine in proportions similar to those of the unmetamorphosed parts of the eugeosynclinal assemblage in the Coast Ranges.

The Santa Catalina Island metamorphic rocks show different degrees of recrystallization and diverse mineral fabrics. Some of the graywackes and greenstones in field exposures are no more sheared than is typical of the unmetamorphosed counterparts on the mainland; others are tightly folded and highly schistose with all original textures and structures destroyed. Measurements of bedding and foliation indicate the two are virtually parallel and the entire section comprises a northwest-trending moderately open syncline. All gradations between graywacke with an incipient development of glaucophane and lawsonite to fully recrystallized foliated quartz-glaucophane-lawsonite schists are present. Similarly, some metamorphosed greenstones show undistorted original diabasic or variolitic textures, whereas other massive and schistose metamorphic rocks, which on the basis of their chemical composition are also believed to have been derived from greenstones, are so completely reconstituted that they show no relict textures. Rhythmically bedded, red metacherts grade to quartz-glaucophane schists. Quartz-piedmontite schists containing crossite also doubtless have resulted from metamorphism of a manganese-rich chert similar to those found in the mainland areas of the Franciscan. Discontinuous veins of quartz, albite, or locally calcite traverse the better developed schists. Examination of more than a hundred thin sections, many of which were of mildly metamorphosed graywacke, failed to reveal any jadeite.

Other extensive areas in which all the Franciscan is metamorphosed lie between Healdsburg and the Pacific Ocean. The largest of these extends from the well-known Junction Schoolhouse locality (about 2 miles southwest of Healdsburg) for at least 20 miles in a northwesterly direction, parallel to the structural

Photo 53. Jadeitized thin-bedded Franciscan graywacke. On State Highway 152, east side of Pacheco Pass, Diablo Range.

grain of the Franciscan in this area. It has an outcrop width of generally between 1 and 2 miles but locally is 2½ miles wide. Throughout its length the belt is apparently bounded by faults. Other somewhat smaller areas of Franciscan metamorphic rock occur near Cazadero (Skaggs quadrangle) and Occidental (Sebastopol quadrangle).

Most of the rocks of the Junction Schoolhouse belt are well-developed quartz-glaucophane-lawsonite schist with or without albite, derived through the metamorphism of graywacke, but also included are tectonic blocks of rocks whose mineral assemblage seems to represent higher temperatures and pressures. Among these are eclogites, glaucophane-eclogites, and garnet-pyroxene-hornblende gneisses. These more unusual rocks, which are not typical of the belt as a whole but are prominently exposed near the Junction Schoolhouse, have been studied and described by Nutter and Barber (1902), Gealey (1951), Switzer (1945, 1951), and Borg (1956); these rocks are discussed in a later part of this report under the heading of eclogite and associated metamorphic rocks. The typical quartz-glaucophane-lawsonite schists are rather monotonous in aspect and mineralogy throughout a section that is nearly 5,000 feet thick as measured across the steeply dipping foliation. They are well exposed in steep roadcuts along the Skaggs Springs-Annapolis road where it crosses the belt between 3 and 5 miles west of Skaggs Springs (Skaggs quadrangle).

In the smaller belt extending northwesterly from Cazadero the metamorphic rocks can be seen along the Cazadero-Fort Ross Road beginning a mile west of Cazadero, and exposures are especially good in the adjacent canyon of Ward Creek southeast of Little Oat Mountain. The rocks of this area provide an interesting contrast to those of the Junction Schoolhouse belt, as most of the glaucophane-bearing rocks west of Cazadero were derived by metamorphism of Fran-

Photo 54. Glaucophane schist derived from graywacke on Cozadero-Fort Ross road, three miles west of Cozadero, Skaggs quadrangle. Foliation parallels bedding which dips to the northeast.

ciscan greenstone and chert accompanied by only small amounts of graywacke. Some of the metagreenstones are unsheared and exhibit well-developed pillow structure, locally with thin blue glaucophane-rich shells around the edges of the pillows, whereas other metagreenstones are more schistose and exhibit both foliation and lineation. The common mineral assemblages include glaucophane, lawsonite, pumpellyite, garnet, aragonite, white mica, and sphene; in varieties derived from chert, stilpnomelane and quartz are abundant.

An area of metamorphosed rock in western Tehama County, shown on figure 18 as "area of phyllites; blueschist(?)," provides another example of fairly widespread development of metamorphic rocks. This area has been studied in reconnaissance by Irwin (1960, p. 37-38) and Kilmer (1961), and some parts have been studied in greater detail by M. C. Blake (oral communication, 1962) and Edward Ghent (1963). The area is shown as blueschist(?) because of the uncertainty regarding the kind and number of metamorphic facies occurring there. Kilmer reports that in this area typical unaltered Franciscan rocks are exposed in the canyon floors and lower slopes, but in going upward the metamorphic grade increases to slate, phyllite, greenschist, and quartz-mica schist on the ridge crests and peaks. Blake reports finding glaucophane-epidote rocks in the high North Yolla Bolly Mountains area. Ghent assigns the schists along the ridge crests in the Hull Mountain and Anthony Peak quadrangles to the blueschist facies because of the widespread occurrence of lawsonite and aragonite, but he reports jadeite is absent. We identified lawsonite in two heavy metagraywackes from the ridges, and also found no jadeite in heavy mineral concentrates. The rocks containing lawsonite are properly assigned to the blueschist facies, but higher grade facies may also be present. The occurrence of the metamorphose rocks above unmeta-

Photo 55. Contorted blueschist formed by metamorphism of thin-bedded graywacke and shale. Near Little Harbor, Santa Catalina Island.

morphosed rocks may be the result of thrusting or may result from overturning of the entire section. Similar relations, with jadeitized graywacke stratigraphically above unmetamorphosed graywacke, were noted in the Pacheco Pass area by McKee (1958a, p. 64).

In contrast to the more extensive belts of glaucophane schists are small patches of mildly metamorphosed glaucophane-bearing metagraywacke or metagreenstone that occur in terranes that are otherwise unmetamorphosed. Locally such schists are reported to have formed along contacts with serpentine and to grade outward into unaltered Franciscan rocks. One locality north of Mount Hamilton has been reported by Crittenden (1951, p. 26); another along Las Aguillas Creek (San Benito quadrangle) was reported by Wilson (1943, p. 195); another in the North Berkeley Hills (San Francisco quadrangle) was reported by Brothers (1954); and Taliaferro (1943a, p. 167) indicates other examples are known to him. In other places the Franciscan is locally metamorphosed even though no serpentine is present. Maddock (1955) mentions three places in the Mount Boardman quadrangle where the change from schist to graywacke took place over a span of 50 to 150 feet. Northwest of the Cazadero metamorphic belt are many areas of greenstone which contain patches exhibiting veining, and local replacement, of the greenstone by a blue amphibole, and also present are some small areas of graywacke containing a little glaucophane.

How common may be areas of local metamorphism involving blueschist facies minerals requires additional observations, but our experience indicates areas where one can definitely observe a gradation from unaltered rock to schist are quite rare. Considering the prevalence of tectonic schist blocks, described in the following section, and the importance of properly interpreting these, one should be unusually cautious in reporting such gradations unless exposures are actually continuous.

Eclogite facies rocks. Dense, green, garnet-bearing metamorphic rocks occurring among the assemblage of Franciscan rocks were first described as eclogites by Holway (1904) and have been studied in detail by Switzer (1945, 1951), Crittenden (1951, p. 25-26), and Borg (1956). Differences of opinion regarding whether or not these rocks are true eclogites have been expressed because the pyroxene is slightly different from the omphacite in eclogite in other areas, and the garnet contains only 20 percent pyrope in contrast to an average content of 39 percent in eclogites described by Eskola (Borg, 1956). Nonetheless, the California rocks seem sufficiently close to eclogites to be so termed in this report. The purest specimens are more than 90 percent omphacite and garnet, and in addition to these two key minerals they generally contain

several percent rutile and some pyrite and chalcopyrite. Closely related to the eclogite, as is indicated by their having a common field occurrence and locally being finely interlayered with eclogite, are hornblende-bearing eclogites, hornblendites, and glaucophane-eclogites. Other rocks related to these are pyroxene-epidote and pyroxene-epidote-glaucophane (garnet-muscovite) rocks. These related rocks differ from the blueschists in texture as well as mineralogy. All are completely crystalloblastic and show no trace of relict texture. Many are coarse grained, and some are gneissic with nearly monomineralic layers of omphacite, hornblende or glaucophane, garnet, and epidote. Some show retrograde metamorphic effects by the alteration of garnet to chlorite, rutile to sphene, or sodic pyroxene to glaucophane.

Many of the rocks described under this heading are cut by sharply bounded, relatively straight veins that are generally less than an inch in width but in places are several inches wide. Most veins are monomineralic, but some contain two or more of the following vein minerals: quartz, albite, glaucophane, lawsonite, pumpellyite, calcite, pyrite, sphene, and apatite. Ptygmatic veins with gradational margins, interpreted to be older than the veins filling fractures, may contain omphacite, hornblende, garnet, apatite, or glaucophane.

The eclogites and related rocks nowhere occur as normal bedrock, but instead are found as isolated, more or less spherical blocks a few feet to a few hundred feet in size (photos 64, 65). Most of these blocks are apparently surrounded by unmetamorphosed Franciscan rocks and obviously are not now in the place where they formed. In places they can be seen to occur in gougey shale in fault zones, in sheared blueschist, or in serpentine, but in these places too they are tectonic inclusions and have been moved from their original environment. On figure 18 we have plotted the locations of some of these blocks to indicate their widespread distribution, but those shown are a small sample of the thousands of blocks that are exposed in the Franciscan terrane. In spite of their abundance and widespread distribution, they are not randomly

Photo 56. Tightly folded blueschist with gently dipping axial planes exposed near the Isthmus on Santa Catalina Island.

Photo 57 (left). Quartz-glaucophane-lawsonite-muscovite schist. This rock contains well oriented prisms of pale colored glaucophane, euhedral tablets of lawsonite, plates of muscovite, and a mosaic of quartz. A little fine-grained magnetite and leucoxene is also present. The schist has formed from a graywacke and contains one of the commonest of the blueschist mineral assemblages. When metamorphism has reached this stage no relict texture remains, the original matrix has disappeared, and all constitutents, including probably even the quartz, are products of the metamorphic reaction. Skaggs quadrangle (59-211).

Photo 58 (right). Quartz-albite-pargasite-stilpnomelane schist. Light areas are a mosaic of quartz and albite. Grey patches elongated parallel to schistosity consist of a blue-green pleochroic amphibole referable to pargasite, muscovite, and a little chlorite. Long dark crystals cutting abruptly across the schistosity are stilpnomelane. Section also contains several precent of sphene, occurring as many small subhedral grains, and a few crystals of garnet. Skaggs quadrangle (57-425).

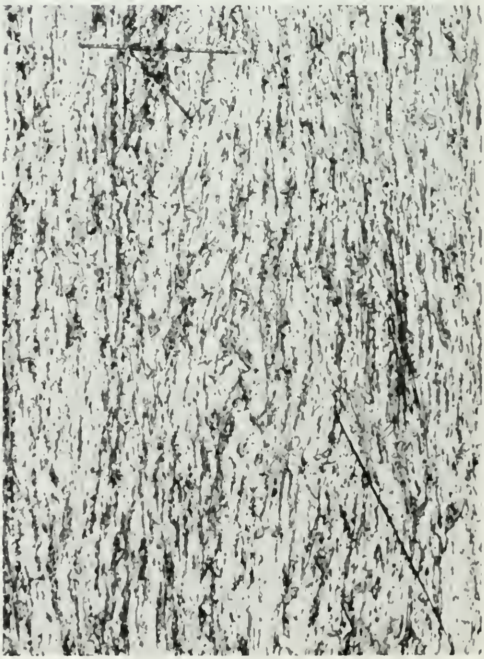
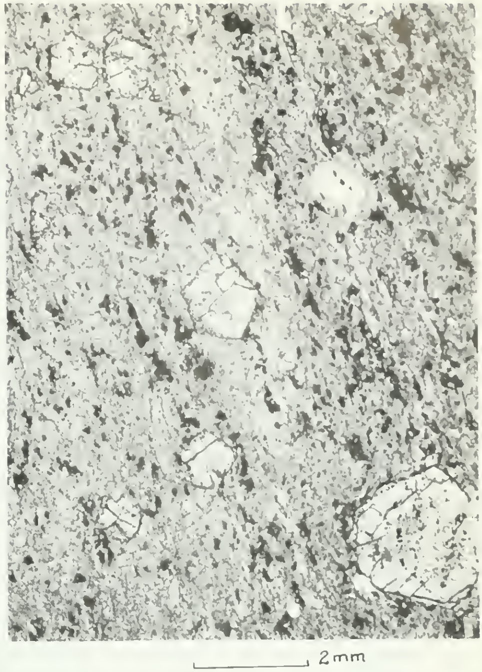


Photo 59 (right). Eclogite. Most of the rock is apple green omphacite with euhedral crystals of garnet showing very slight retrograde alteration to chlorite. Dark patches are sphene, which occurs mantling rutile, as larger porphyroblastic crystals, and as abundant aggregates of small crystals. A little glaucophane and muscovite are present; they generally occur together and in most places with chlorite. Rock analysis given in table 14, column 9. Skaggs quadrangle (59-193).



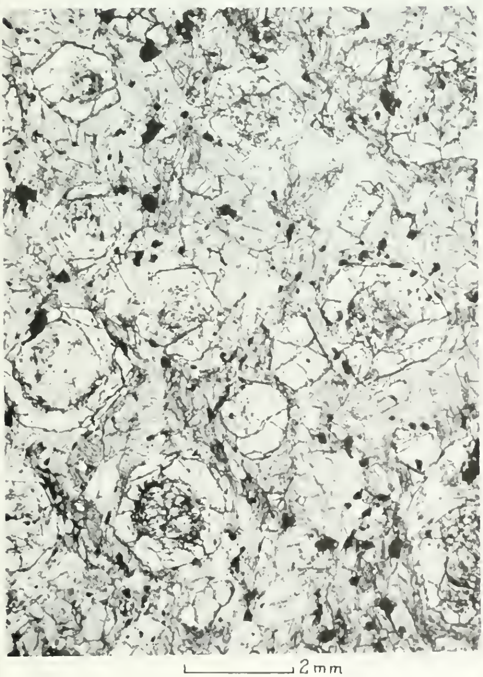


Photo 60 (left). Garnet amphibolite. Predominant mineral is an amphibole which in most crystals grades from a hornblende in the central part to glaucophane at the margin. Garnet occurs in euhedral porphyroblasts, and green omphacitic pyroxene occurs as subhedral crystals and radial growths. Muscovite and chlorite are present in small amounts and some of their relations suggests both may be retrograde. Rutile is conspicuous and in many places is coated with sphene. Although an amphibole predominates in this rock other features of the mineralogy and texture are much like those of the Franciscan eclogites cf. figure. Skaggs quadrangle (60-341).

Photo 61. Garnet glaucophane schist. This rock is composed chiefly of well-oriented subhedral prisms of glaucophane with which are stubby prisms of pale epidote and plates of muscovite. Garnet porphyroblasts enclose many grains of quartz, and they appear to have forced aside the glaucophane and epidote forming augen that are largely filled with quartz. Most dark areas are clots of leucoxene, some of which contain central cores of rutile, but some black areas are magnetite. Skaggs quadrangle (59-639).

Photo 62. Tectonic block of glaucophane schist cut by quartz veins. Skaggs quadrangle, two miles south of Hedgpeth ranch.

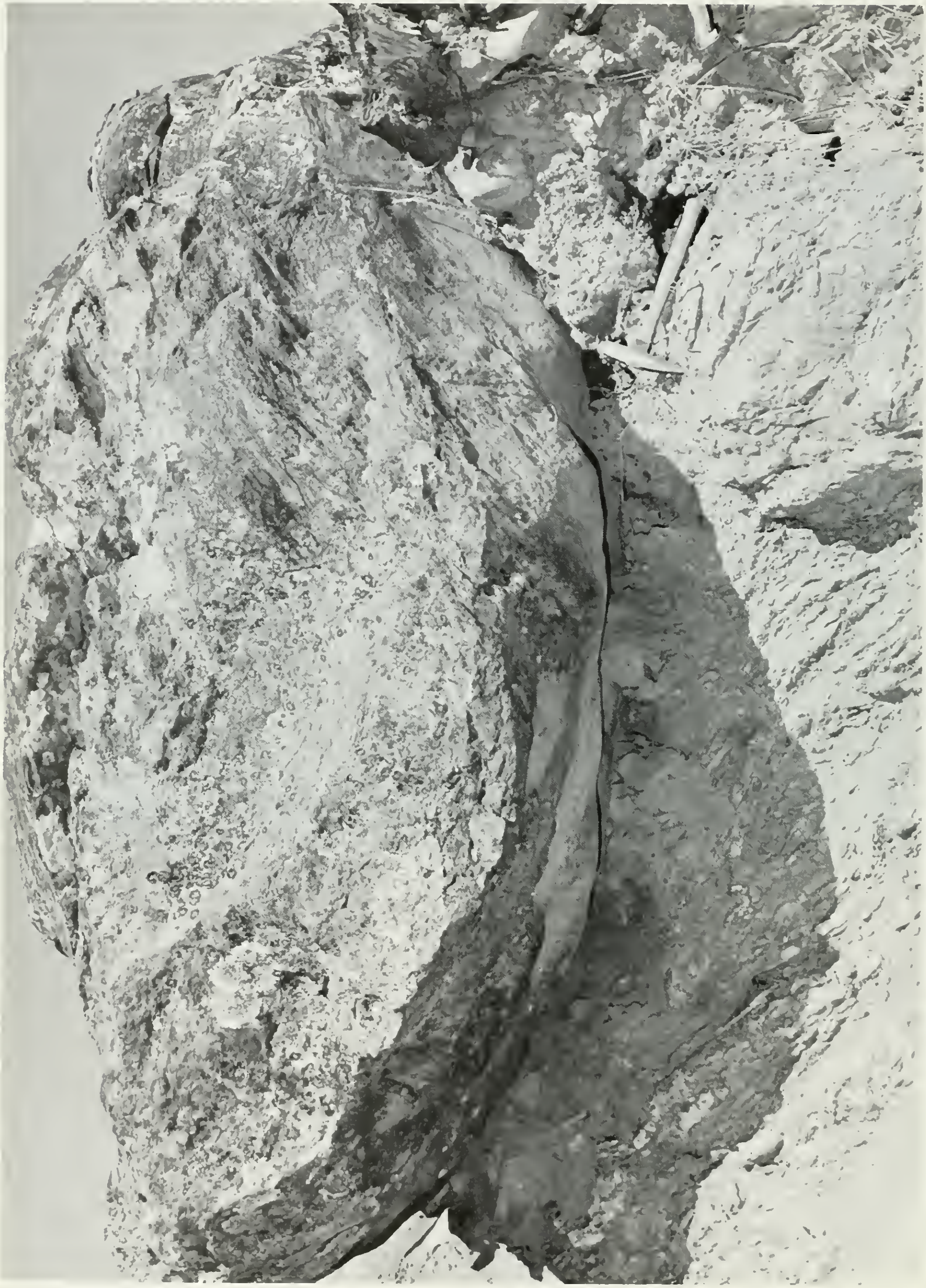


Photo 63. Residual tectonic boulder of glaucophane schist lying on blueschist formed from graywacke. Skaggs quadrangle.

Photo 64. Tectonic block of glaucophane schist, showing typical spheroidal shape, surrounded by metagraywacke. Foliation largely parallels rounded surface, showing that this shape is primary and not due to weathering or erosion. Skaggs quadrangle.

Photo 65. Large tectonic block of gneiss made up of layers of eclogite, glaucophane-eclogite, glaucophane-epidote rock, and glaucophane-garnet rock, cut by veins of lawsonite and wrapped in a peripheral shell of chlorite-actinolite schist. Note person standing at base of block in center of photograph. Spy Rock road near east edge of Leggett quadrangle.

distributed. In some areas, like the coastal belt, the tectonic blocks are rare or absent, and even in areas where they are common they occur in greatest abundance scattered through broad linear belts believed to be major shear zones.

Most of the tectonic blocks of metamorphic rock show a prominent planar foliation and also have a strong linear orientation. In some cases the foliation near the margin swings abruptly to parallel the block boundary. Surrounding many of the blocks, including those not engulfed in serpentine, is a peripheral shell a few feet thick of chlorite-actinolite schist, in which the mineral orientation is parallel to the margin of the block. The veins found within the eclogite, or other core rock, do not extend through this chloritic marginal shell. In a few places the boundary of the massive eclogite is sharply offset by a fault of small displacement, but the resulting angular margin is smoothed out by a flexure in the chloritic shell. Other blocks with little or no chloritic shell are smooth, locally even polished, and in effect are enveloped by a slickensided surface. An unusual example showing deep gouges and striae with several different orientations is shown in photo 66. Although tectonic abrasion and weathering tends to obliterate the soft chloritic shell or slickensided surfaces, such features have been observed on many blocks, and their existence further substantiates the conclusion that the blocks were brought into their present position by tectonic means and are not the result of metamorphism in place.

Although rocks of the eclogite facies occur only in tectonic blocks, not all the tectonic blocks found in the Franciscan consist of rocks of the eclogite facies. Many of these blocks are blueschists, which in mineralogy and texture are like the normal blueschists that form the bedrock over extensive areas. Commonly these blocks are glaucophane-bearing rocks, but jadeitized graywacke also occurs in this manner and, because of the difficulty of recognizing it, may be more common than it is now known to be. Still other tectonic blocks of similar size and shape, and in places showing tectonically abraded surfaces, consist of unmetamorphosed Franciscan graywacke, chert, or greenstone.

Relation of metamorphic rocks to serpentine. Rocks of the blueschist facies occur in the California Coast Ranges, as in most other places throughout the world, in areas that also contain serpentine. Some blueschists, as well as eclogites and associated rocks, are found as inclusions in serpentine, and many others occur close to the margins of serpentine masses. This association of blueschist and serpentine is so prevalent that it has led some geologists to the belief that the blueschists of the Coast Ranges have formed as the result of pneumatolitic alteration caused by the serpentine or by ultramafic magma (Taliaferro, 1943a, p. 159-182; Crittenden, 1951, p. 25-26; Switzer, 1945, p. 8).

In the Junction Schoolhouse and Cazadero metamorphic belts west of Healdsburg, and on Santa Catalina Island, the evidence that the blueschists result from some widespread form of metamorphism and are not genetically related to ultramafic masses is compelling. All these areas contain a little serpentine, but not enough to have caused the extensive metamorphism. In addition, detailed mapping of these areas indicates a complete independence between the occurrences of schist and occurrences of serpentine, and the metamorphic grade does not change in going outward from the serpentine contacts.

Elsewhere in the California Coast Ranges we found, for every schist mass close enough to a serpintine mass to be related to it in origin, perhaps ten schist masses too distant from serpentine masses to be related. It has been suggested that many of these distant schist masses are underlain by serpentine that does not crop out, but statistically this suggestion becomes quite improbable. Even some schist masses found in contact with serpentine can be demonstrated not to represent contact metamorphism of the intruded rock because these masses have formed from source rocks different from those bordering the serpentine; for example, metagreenstones along a contact between serpentine and graywacke. Other supposed contact zones include a jumble of metamorphic rocks which, because of their mineral assemblages, must have formed under dissimilar pressure-temperature conditions. It is thus clear that most of the isochemically metamorphosed Franciscan rocks were not formed by any process, either pneumatolitic or otherwise, related to serpentine or ultramafic intrusions, and we doubt that serpentine is in any way responsible for the origin of these metamorphic rocks.

Age of the metamorphism. The time of metamorphism of both bedrock blueschists and tectonic blocks of glaucophane-epidote-garnet gneiss in the Ward Creek area has been investigated by isotope methods by Lee and colleagues. They report (Lee and others, 1963), "The isotope age determinations made on muscovites obtained from these schists gave the following results: potassium-argon ages for two bedrock schists gave 135 and 128 million years; three samples from the tectonic blocks gave an average potassium-argon age of 142 million years; a single rubidium-strontium age determination on muscovite from these tectonic blocks gives an age of 149 million years." These ages indicate this metamorphism took place in Late Jurassic or Early Cretaceous time (Kulp, 1961). Similar ages were found for 8-10 samples from various bedrock localities by the geochronology group at the University of California according to G. H. Curtis (oral communication, April 1963).

Origin of the metamorphic rocks. The Franciscan metamorphic rocks of the zeolite and blueschist facies, including jadeitized metagraywacke, are believed to be normal Franciscan sedimentary and volcanic rocks isochemically metamorphosed, chiefly as a result of load metamorphism under conditions of abnormally low temperatures relative to pressures. The distribution of

Photo 66. Striae on chlorite-actinolite envelope around tectonic block of glaucophane schist. Skaggs quadrangle.

the blueschists in linear belts suggests that some other factor, perhaps stress, may have been effective in initiating mineral growth in the low-temperature, high-pressure environment. The eclogites and related rocks may originally have been Franciscan sedimentary and volcanic rocks downwarped to extreme depths, or they may be rocks from beneath the Franciscan; in either case they have been moved upward relative to the other rocks of the area either tectonically or as inclusions in ultramafic masses.

The rocks of the zeolite facies have been recently discussed by Coombs and others (1959) and Coombs (1960) as well as by Fyfe, Turner, and Verhoogen (1958) and present no special problem. These rocks occur under normal regional or load metamorphism at temperatures generally less than 300°C and at moderate pressures, but they may also be formed by diagenesis. The only mystery regarding these rocks in the Franciscan is why they are not more widespread, or at least have not been more widely recognized.

The rocks of the blueschist facies in the Franciscan of California, and in other parts of the world as well, have been the subject of many papers and much difference of opinion. Because of the general presence of striking blue amphibole or jadeite, geologists have tended to think of these rocks as either soda-rich or enriched in soda. The many chemical analyses now available, however, clearly indicate most of the Franciscan blueschists are chemically similar to sedimentary or volcanic rocks of the Franciscan, and no addition of soda is required for the formation of the blueschists (see table 14a, b, and fig. 20). Similar conclusions have been reached by other geologists who studied blueschists from this area, Japan, or the entire world (Washington, 1901; Smith, 1906; Miyashiro and Banno, 1958; Ernst, 1959).

When it is recognized that rocks of the blueschist facies do not differ chemically from rocks of the more common greenschist facies, if one is to explain the origin of blueschists one must call upon some general

condition of metamorphism that is unusual but nonetheless repeated during geologic time in many eugeosynclinal accumulations throughout the world. Various possibilities are: abnormally high pressure linked with moderate temperature, abnormally high or low water pressure, abnormal oxygen pressure, high directed stress, or combinations of these. Because of their general high density, the presence of lawsonite, jadeite, and aragonite, and their restriction to certain eugeosynclinal environments, it seems reasonable to explain the development of blueschists rather than greenschists as due to unusually high pressures, resulting from deep burial, and low temperatures, resulting from accumulation and downwarping taking place so rapidly that a normal thermal gradient was not established. The role of directed stress, or of abnormally high pressure developed in a local area as a result of tectonic movements, is difficult to assess. The low competence of the Franciscan that results from its intimately broken character, and its plasticity even under relatively shallow loads as is indicated by its flowage to form diapir intrusions, leads us to believe that the Franciscan is unlikely to have sufficient strength to permit the buildup or transmission of stresses amounting to more than a small fraction of the pressure due to load. However, the limited occurrence of at least the glaucophane-bearing blueschists in belts that parallel the prevalent directions of shearing, suggests even a small increase in stress may have been operative in triggering the metamorphism of rocks already under high lithostatic pressure.

Figure 21 is an attempt to reconcile the available experimental and field evidence regarding the pressure-temperature environment for the zeolite, blueschist, and greenschist facies assemblages. While exact temperatures and pressures are indicated, one must be fully aware that every boundary line in the diagram is in nature essentially a transition zone and that scarcely any point on the lines can be fixed with certainty. Pressure-temperature boundaries between natural mineral phases are subject to variations due to the presence of minor components in the reacting phases or to their involving reactions that in nature are linked chemically with other reactions, as well as being modified by a variation in water, oxygen, or in some cases, carbon dioxide pressure, with the result that P-T diagrams for complex natural systems cannot be made precise. Similarly, great uncertainties exist as to what is the true slope of a maximum, minimum, or "normal" thermal gradient (Birch, 1955; Turner and Verhoogen, 1960, p. 436-439). However, in spite of multiple uncercertainties the diagram serves to show what are believed to be the general relations of various facies fields to each other, to approximate pressure-temperatures conditions, and, indirectly, to geologic environment during the time of metamorphism.

The figure shows two main fields of metamorphic rocks separated by a line of "maximum thermal gradient from conduction" and designated as "Thermal

Figure 20. Location of analyzed metamorphic rocks listed in tables 14a and 14b.

Metamorphism" and "Load Metamorphism." The maximum thermal gradient line is intended to separate a lower area, in which the flow of heat is dominated by normal rock conduction, from an upper area, in which heat is also added by the inflow of hot gases, water, or magma. The area of load metamorphism is further subdivided into two fields separated by a line intended to indicate the lower limit of thermal gradient existing in rocks that have reached equilibrium insofar as temperature is concerned. Above the line is a field occupied by the usual sequence of facies of regionally metamorphosed rocks. Below this line is a field of low temperatures relative to pressures, into which rocks will not normally fall unless they have accumulated rapidly, subsided rapidly, or both. The blueschist facies is believed to be entirely in this latter field.

Boundary lines between zeolite, blueschist, and greenschist facies are the postulated stability boundaries between several essentially calcium-aluminum silicates—laumontite (or prehnite or pumpellyite), lawsonite, and epidote. The lines as drawn fit the avail-

Table 14a. Analyses and molecular norms of Franciscan metamorphic rocks: Metamorphosed sedimentary rocks.

	1	2	3	4	5	6	7	8	9	10
SiO_2	70.61	69.14	70.04	60.63	68.2	70.0	67.1	74.48	80.21	67.5
TiO_2	0.53	0.37	0.14	1.21	0.62	0.51	0.55	--	--	0.5
Al_2O_3	11.99	15.08	13.88	15.98	13.00	12.0	13.6	9.15	7.99	13.5
Fe_2O_3	1.59	1.51	0.91	1.11	1.6	1.0	1.3	1.41	--	1.2
FeO	2.22	0.84	2.26	3.62	2.7	2.8	3.5	4.12	3.35	3.0
MnO	0.05	0.03	0.07	0.11	0.08	0.08	0.06	--	--	0.1
MgO	2.82	1.08	2.11	4.07	2.4	3.1	2.4	3.04	1.54	2.2
CaO	2.41	2.79	1.79	4.34	2.0	2.2	2.6	2.84	1.10	2.4
Na_2O	2.86	5.31	4.01	3.59	2.2	2.6	1.4	2.24	5.97	3.6
K_2O	1.64	1.28	0.97	1.00	2.2	2.0	2.0	0.43	0.22	1.7
H_2O+	2.81	1.96	3.15	3.36	3.2	2.7	4.0	2.06	0.74	2.5
H_2O-	0.20	0.08	0.25	0.31	0.50	0.16	0.33	0.08		0.4
CO_2	0.03	--	0.07	0.42	1.0	0.38	<0.05	--	--	0.8
P_2O_5	0.07	0.12		0.01	0.10	0.10	0.19	--	--	0.1
Total	99.83	99.59	99.65	99.76	99.8	100.00[a]	99.6[b]	99.85	101.12	99.5
Density	2.86	2.91	2.91	2.96	2.75	2.79	2.77	--	--	--

MOLECULAR NORM-CATANORM

	1	2	3	4	5	6	7	8	9	10
Q	37.2	25.1	33.6	19.4	40.4	36.4	41.3	45.4	--	31.3
or	10.0	7.5	6.0	6.0	14.0	12.0	12.5	2.5	--	10.6
ab	27.0	48.5	37.5	33.5	21.0	24.5	13.5	21.0	--	33.8
an	11.0	13.0	9.0	20.0	2.5	8.0	12.5	14.8	--	6.2
C	1.9	0.4	3.6	2.3	7.0	3.2	5.8	--	--	4.0
en	8.2	3.0	6.0	11.6	7.0	9.0	7.2	8.8	--	6.3
fs	1.6	--	3.0	3.2	2.2	3.8	3.2	6.2	--	3.1
mt	1.8	1.2	0.9	1.2	1.8	0.8	1.5	1.4	--	1.3
il	0.8	0.6	0.2	1.8	1.0	0.6	0.8	--	--	0.8
hm	--	0.3	--	--	--	--	--	--	--	--
ap	0.3	0.3	--	--	0.3	0.3	0.3	--	--	0.4
cc	0.2	--	0.2	1.0	2.8	1.0	0.2	--	--	2.0
py	--	--	--	--	--	0.4	1.1	--	--	--
%An in plag	29	21	19	37	11	25	48	41	--	15

1. Jadeitized metagraywacke, Berkeley Hills, Contra Costa County, Calif. (Bloxam, 1956, p. 493). Analysis by E. H. Oslund.
2. Jadeitized metagraywacke, Valley Ford, Sebastopol quadrangle, Sonoma County, Calif. (Bloxam, 1956, p. 493). Analysis by E. H. Oslund.
3. Jadeitized metagraywacke, Point Blunt, Angel Island, Marin County, Calif. (Bloxam, 1960, p. 559). Analysis by T. W. Bloxam.
4. Quartz-glaucophane schist (from graywacke), Point Simpton, Angel Island, Marin County, Calif. (Bloxam, 1960, p. 567). Analysis by T. W. Bloxam.

5-7. By rapid rock analysis method described in U. S. Geol. Survey Bull. 1036-C.

5. Jadeitized metagraywacke, 800 ft southeast of Campbell Point, Angel Island, Marin County, Calif. Analysis by P. L. D. Elmore, S. D. Botts, I. H. Barlow, and M. D. Mack.
6. Jadeitized metagraywacke, Pacheco Pass, along U. S. Highway 152 at B.M. 190, Pacheco Pass quadrangle, Calif. Collected by R. G. Coleman. Analysis by P. L. D. Elmore, S. D. Botts, I. H. Barlow, and Gillison Chloe.
7. Jadeitized metashale, same locality as no. 6 above. Collected by R. G. Coleman. Analysis by P. L. D. Elmore, S. D. Botts, I. H. Barlow, and Gillison Chloe.
8. Quartz-glaucophane schist, Little Harbor, Santa Catalina Island, Los Angeles County, Calif. (Washington, 1901, p. 48). Analysis by H. S. Washington.
9. Quartz-glaucophane schist (metachert), Angel Island, Marin County, Calif. (Ransome, 1894, p. 231). Analysis by F. L. Ransome.
10. Average Franciscan graywacke, column 1, table 2, of this report.

[a] Also includes S = 0.18.
[b] Also includes S = 0.39.

able, though as yet very limited, experimental data for pure calcium-aluminum silicates (Fyfe, Turner, and Verhoogen, 1958; Coombs and others, 1959). Iron, however, also enters into some of these reactions since pumpellyite normally contains some iron, and epidote rather than zoisite is the common epidote-group mineral. Until experimental data are available for the coupled reactions involved (Fyfe, Turner, and Verhoogen, 1958, p. 151-153), the exact position of the facies boundaries cannot be fixed. Also shown are possible field boundaries for the sodium-aluminum silicates—analcite, albite, and "jadeite," with the latter in quotes because Ca, Mg, and Fe are normally present and are required to bring the analcite-"jadeite" boundary to the low pressure indicated (Robertson and others, 1957; Coleman, 1961). The position of the calcite-aragonite boundary is believed to be quite accurate as this is a simple phase change, and both ends of the line have been determined experimentally (Jamieson, 1953; MacDonald, 1956; Clark, 1957). The occurrence of aragonite rather than calcite in the blueschists (Coleman and Lee, 1962) is particularly significant because the calcite-aragonite boundary is nearly parallel and considerably below the lower limit of the field of "normal" thermal gradients. Its occurrence as a stable mineral in the blueschist requires an environment of abnormally low thermal gradient. The eclogite line is drawn to agree with the experimental work of

Table 14b. Analyses and molecular norms of Franciscan metamorphic rocks: Metamorphosed igneous rocks.

	1	2	3	4	5	6	7	8	9	10
SiO_2	49.68	48.29	51.28	49.17	49.12	48.26	47.99	45.8	49.5	49.1
TiO_2	1.31	1.37	2.96	2.51	0.61	2.51	2.62	3.2	2.0	2.0
Al_2O_3	13.60	14.62	12.04	12.19	14.99	12.81	12.50	13.2	12.7	13.8
Fe_2O_3	1.86	0.84	2.98	1.10	0.97	4.10	3.40	6.4	4.9	3.9
FeO	8.61	8.37	10.54	10.88	9.21	9.15	11.12	9.1	5.2	7.7
MnO	0.04	0.22	0.38	0.29	0.07	0.16	0.31	0.23	0.24	0.2
MgO	6.26	8.33	7.76	6.83	6.58	6.71	6.11	5.4	7.0	6.1
CaO	10.97	10.24	3.95	10.76	10.65	8.76	12.16	11.0	11.7	9.4
Na_2O	3.09	2.47	4.49	2.47	2.58	2.93	2.98	4.3	4.9	3.3
K_2O	0.12	0.13	0.52	0.32	0.90	0.10	0.21	0.04	0.54	0.4
H_2O+	3.84	4.93	2.28	3.58	4.11	3.47	0.44	1.7	1.5	2.4
H_2O-		0.12	0.17	0.27	0.19	0.32	0.08	0.09		0.4
CO_2	--	--	--	0.02	--	0.01	--	<0.05	<0.05	0.8
P_2O_5	0.21	0.12	0.38	--	0.12	0.36	--	0.17	<0.05	0.2
Total	99.59	100.05	99.73	100.39	100.10	99.65	99.92	100.7	100.3	99.7
Density	--	3.11	3.20	3.20	3.15	3.21	3.47	3.32	--	--

MOLECULAR NORM-CATANORM

	1	2	3	4	5	6	7	8	9	10
Q	0.2	--	--	0.6	--	3.3	3.3	--	--	2.4
or	0.5	1.0	3.0	1.5	5.5	0.5	1.0	0.5	3.5	2.5
ab	29.0	23.5	42.0	23.5	24.0	28.0	22.0	40.0	44.0	30.5
an	24.2	29.5	11.5	22.5	28.0	23.0	20.8	17.0	11.0	22.7
di	25.2	18.4	4.8	27.2	21.2	16.0	32.8	29.6	36.8	16.0
hy	16.4	19.4	15.2	19.8	11.2	20.0	12.4	--	--	16.2
ol	--	5.1	--	--	7.8	--	--	4.5	2.1	--
mt	2.1	0.9	3.3	1.2	1.1	4.5	3.8	6.9	5.1	4.2
il	1.8	2.0	4.2	3.6	1.0	3.6	3.8	4.6	2.8	3.0
ap	0.5	0.3	0.8	--	0.3	0.8	--	0.5	0.3	0.5
cc	--	--	--	--	--	0.2	--	0.2	0.2	2.0
Silica deficiency	--	--	--	--	--	--	--	(−3.6)	(−5.9)	--
%An in plag	45	56	21	49	54	45	49	30	20	43

1. "Zoisite-glaucophane schist," Sulphur Bank, Lake County, Calif. (Becker, 1888, p. 104). Analysis by W. H. Melville.
2. Glaucophane-lawsonite-pumpellyite schist, Junction School area, Healdsburg quadrangle, Sonoma County, Calif. (Borg, 1956, p. 1568). Analysis by W. Herdsman.
3. Glaucophane-garnet-lawsonite schist, Junction School area, Healdsburg quadrangle, Sonoma County, Calif. (Borg, 1956, p. 1568). Analysis by W. Herdsman.
4. Glaucophane-omphacite-garnet schist, Valley Ford, Sebastopol quadrangle, Sonoma County, Calif. (Bloxam, 1959, p. 98). Analysis by T. W. Bloxam.
5. Glaucophane-lawsonite-pumpellyite schist, Valley Ford, Sebastopol quadrangle, Sonoma County, Calif. (Bloxam, 1959, p. 98). Analysis by T. W. Bloxam.
6. Glaucophane-lawsonite-(jadeite?) metadiabase, Point Simpton, Angel Island, Marin County, Calif. (Bloxam, 1960, p. 564). Analysis by T. W. Bloxam.
7. Eclogite, Valley Ford, Sebastopol quadrangle, Sonoma County, Calif. (Bloxam, 1959, p. 98). Analysis by T. W. Bloxam.
8-9. By rapid rock analysis method described in U. S. Geol. Survey Bull. 1036-C. Analyses by P. L. D. Elmore, S. D. Botts, I. H. Barlow, and Gillison Chloe.
8. Eclogite with glaucophane, Ward Creek south of Little Oat Mountain, Cazadero quadrangle, Sonoma County, Calif.
9. Eclogite, 1 mile south of Moffitt Ranch, Tombs Creek quadrangle, Sonoma County, Calif.
10. Average of least altered Franciscan greenstones, column 16, table 4 of this report.

Yoder (1950), Kennedy (1959), and Yoder and Tilley (1961), and in the low-pressure area this line falls approximately along a line representing minimum temperatures relative to pressures that can be reasonably supposed to exist in the earth.

A field for the occurrence of glaucophane is also shown on the diagram, but its boundary is entirely inferred on the basis of the occurrence of glaucophane, and minerals associated with glaucophane, rather than on experimentally determined limits of stability. Ernst (1959, 1961) has formed glaucophane experimentally at temperatures between 750° and 870°C and pressures up to 2 Kb but, because of the sluggishness of the reactions involved, has not been able to determine its lower limit of stability. Its upper limit of stability as determined experimentally ranges between about 850°C at 175 bars vapor pressure and 870°C at 2,000 bars, indicating it is not itself a high-pressure or pressure-sensitive mineral.

Factors considered in indicating the stability field of glaucophane are therefore mineral associations and geologic environment. Because of its close association with lawsonite and aragonite, glaucophane is known to be stable in the abnormally low-temperature high-pressure environment of the subnormal-gradient field; because of its scarcity in greenschists, we assume that glaucophane does not form in most of the normal thermal gradient field even though this appears to be contradicted by some of the experimental data. Glaucophane occurs in stable association with "jadeite" and

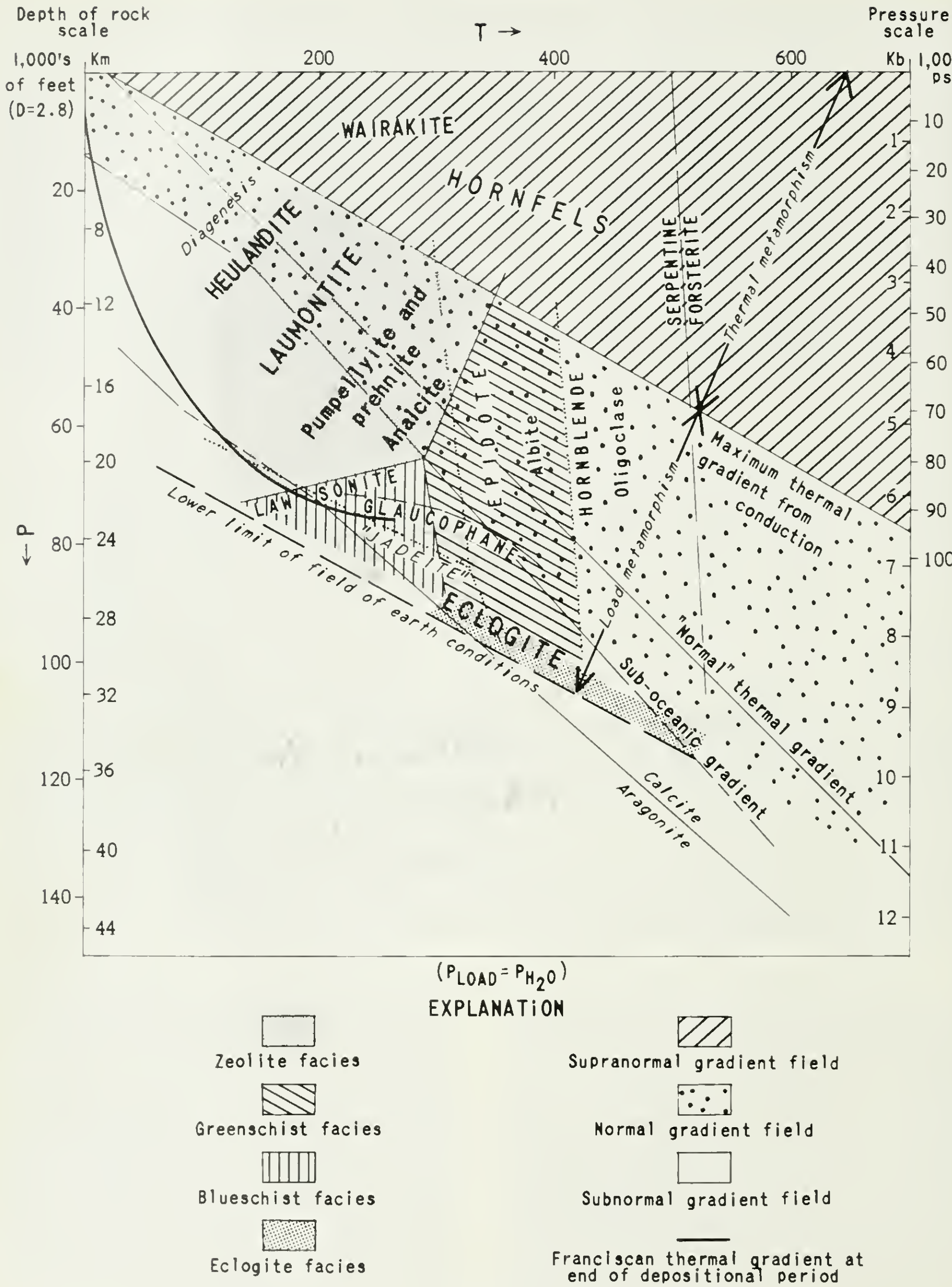


Figure 21. Possible P-T fields for some blueschist and related metamorphic facies.

albite, and with pumpellyite(?), lawsonite, and epidote, though we know of no rocks in which it occurs with laumontite. Its absence from lawsonite-bearing rocks in New Zealand suggests its formation requires a bit higher pressure at a given temperature than is required for the formation of lawsonite. Its apparent stable association with omphacite indicates its high-pressure limit may be close to, or within, the environment in which some eclogites form.

The glaucophane field obviously is not the same as the blueschist field as the former also includes part of the greenschist field and probably extends into the hornblende (almandite)-oligoclase field shown on the diagram. The occurrence of glaucophane with assemblages falling outside of the blueschist field is less common than is its occurrence with lawsonite. This is probably because it is less common for rocks to reach the required P-T field, and then be uplifted to where we can see them, without their being converted to the assemblages of the normal gradient field.

It should be noted that the glaucophane schists occupying extensive areas in the Franciscan terrain and believed to result chiefly from load metamorphism are stable assemblages occurring within the field of blueschist on the diagram. Eclogites, or glaucophane-epidote assemblages occurring as tectonic inclusions, are rocks representing higher temperature-pressure conditions and are partly unstable in the blueschist facies field. Glaucophane-eclogites, which also occur as tectonic inclusions, have been explained as caused by retrograde metamorphism of eclogites in the blueschist facies environment, and certainly some have textures suggesting such an origin. Others, however, do not have obvious retrograde textures and seem to be stable associations formed in the transition zone between blueschist and eclogite.

Veins which cut the blueschists may be expected to contain minerals that were stable under the prevailing temperature-pressure conditions, but veins along fractures in the tectonic blocks generally indicate temperatures and pressures lower than those under which the metamorphic rock formed—for example, pumpellyite veins cutting eclogite or glaucophane-eclogites.

Geologic implications of the blueschists. If the facies diagram (fig. 21) is reasonably correct, it has interesting implications regarding several aspects of the geologic history of the metamorphosed parts of the Franciscan. For the rocks to have reached the blueschist facies environment, sedimentation and downwarping must have taken place so rapidly that normal heat flow from below, plus heat generated by radioactivity within the sequence, was unable to reach normal steady state conditions, resulting in abnormally low temperature relative to pressure. Because of uncertainties regarding thickness and length of time allowable for the accumulation of the Franciscan, it is not possible to check this inference by comparing it with a known period of accumulation or downwarping based on accurate knowledge of its beginning and ending. However, the older pre-Knoxville part of the Franciscan, which is apparently the only part that contains extensive areas of rocks of the blueschist facies, is known to be very thick and suspected to have been deposited during the brief interval between the deposition of the Galice and Mariposa Formations and the deposition of the Knoxville Formation, a span that allows only a few millions of years for its accumulation.

Another implication of the diagram is that the lowest part of the Franciscan reached an apparent depth of more than 20 km or 70,000 feet. Part of this depth may be initial owing to deposition in an oceanic deep, part represents the thickness of the eugeosynclinal accumulation, and part may represent downbuckling. Considering all the possibilities our best inference is that the accumulation itself is very thick, probably over 50,000 feet thick. Unfortunately this figure cannot be checked by measurements of total or partial stratigraphic sections because of structural complexities previously described. A thickness of 50,000 feet is greater than has generally been attributed to the Franciscan, but this thickness does not appear to be excessive.

If the accumulation of Franciscan rocks at the time of metamorphism was 50,000 feet thick and possessed an abnormal thermal gradient, it is of interest to attempt to draw a reasonable thermal gradient line on figure 21. The upper end of the thermal gradient line will be at the top of the eugeosyncline and at a temperature near 0°C. The pressure might be the water pressure at the base of an oceanic deep, roughly equivalent to a rock load of 15,000 feet. The occurrence of aragonite, rather than calcite, as the stable calcium carbonate in some of the blueschists requires the thermal gradient line to pass below the well-established calcite-aragonite phase boundary shown on the figure. A thermal gradient curve of appropriate shape has been drawn starting from 0°C and falling below the calcite-aragonite boundary near the zeolite-blueschist facies boundary. For such a curve to approximate the actual thermal gradient in the Franciscan requires the sedimentation and downwarping to have taken place in a period of a few million to a few tens of millions of years (Grossling, 1959), though just how brief the period must be depends on what assumptions are made regarding heat flow into the pile, heat generated within the pile, and heat gains or losses due to metamorphic reactions. It may be significant that these rocks lack K-feldspar and therefore would have an abnormally low rate of heat generation due to radioactive decay.

A further, and equally important, implication of the diagram is that blueschists formed in a field of abnormally low temperature relative to pressure will, during the passage of time in which the thermal gradient approaches a more normal gradient, or a state of heat equilibrium, pass from the field of blueschists into the

field of greenschists, or in the extreme case, into the almandine-amphibolite facies. As Franciscan blueschists do not normally show any sign of having been in the greenschist environment, we may infer that they not only reached considerable depths rapidly but also were subsequently uplifted to higher levels before a normal thermal gradient was established. The fact that aragonite is present and has not inverted to calcite not only indicates very rapid subsidence but also clearly indicates rapid uplift and erosion (Brown and others, 1962). This conclusion is compatible with what can be inferred from the geologic history of the Franciscan and its structural relation to other units.

The diagram also has implications regarding the role contact metamorphism, by either mafic or ultramafic rocks, might play in the formation of blueschists. An intrusive mass might raise the temperature of its walls by many hundreds of degrees, but it cannot be expected to have more than very minor effect on the pressure. The diagram clearly shows that *raising the temperature would not result in the formation of blueschists under any pressure*, and although contact metamorphism might result in the formation of greenschists, or higher-grade assemblages, it cannot be expected to form blueschists. In the New Almaden area (Bailey and Everhart, 1964), where both blueschists and amphibolites occur in the Franciscan, the amphibolites border and grade out from serpentine masses, whereas the blueschists occur as tectonic inclusions remote from the serpentine.

Part II -- Significance of the Franciscan in the Geology of the Coast Ranges

The things that must be known about the assemblage of Franciscan rocks before its significance in the geology of the Coast Ranges can be understood may be broadly divided into two categories: (1) the lithic composition of the assemblage, and what the lithic components indicate about the depositional environment; and (2) the relation of these rocks to different bordering rocks of similar age, and the paleogeographic or tectonic features that have brought about these relations. The data presented in the first part of this report fall into the first category. They indicate that the Franciscan is composed chiefly of a very thick accumulation of somewhat unusual sedimentary and volcanic rocks that seem to have been deposited rapidly in deep water in a subsiding trough, presumably quite close to an equally rapidly eroding landmass or landmasses. Locally, the thick pile was intruded by serpentine, and its deeper parts were metamorphosed. The second part of this report will discuss the relation of these Franciscan rocks to other rocks of the Coast Ranges. To provide the proper framework for this discussion, we will first consider the controversial age of the Franciscan, and then describe briefly another assemblage of rocks of similar age occurring chiefly in the Great Valley and referred to herein as the Great Valley sequence. Following this, data regarding the similarities and differences between these two coeval assemblages will be given. Once these differences are established, we describe the major structural elements of the Coast Ranges and point out some of the anomalous relations of the two assemblages. In summary, we suggest some solutions to the major problems brought about by the juxtaposition of the coeval Franciscan rocks and Great Valley sequence either through original deposition or tectonic displacement.

FOSSILS FROM THE FRANCISCAN

Megafossils are remarkably rare in the Franciscan, and in spite of the wide distribution and great thickness of the unit, they have been found in only about a dozen localities. On the other hand, microfossils, including Foraminifera in limestone and Radiolaria in chert, are locally very abundant. Of the microfossils only the Foraminifera have yielded diagnostic age determinations, and unfortunately the foraminiferal limestones are restricted to a small part of the outcrop area of the Franciscan rocks.

Ages ranging from Late Jurassic (Tithonian) to Late Cretaceous (Campanian) are indicated by fossils found in rocks that have been assigned by various geologists to the Franciscan. The stages represented by these fossil finds are shown in table 15, which also includes a complete listing of the European stage names used in this report. The most abundant and reliable age determinations have come from rocks on the San Francisco peninsula and from contiguous areas to the north and south. Rocks in these areas have been consistently dated as mid-Cretaceous. Elsewhere, fossils are scarcer, and some large areas of Franciscan rocks have yielded little or no diagnostic paleontologic data. The kinds of fossils that have been found, and their respective age assignments, are tabulated in tables 16 and 17; their distribution is shown on figure 22.

Table 15.

Stage assignments of fossils found in Franciscan rocks.

System	Series	Stage		Franciscan Fossils	Radiometric ages in years-before present (Kulp, 1961)
Cretaceous	Upper	Maestrichtian			72
		Campanian		X?	
		Santonian			84
		Coniacian			90
		Turonian		X	
		Cenomanian		X	110
	Lower	Albian		X	120
		Aptian			
		Barremian	Neocomian		
		Hauterivian			
		Valanginian		X	
		Berriasian			135
Jurassic	Upper	Tithonian		X	
		Kimmeridgian			
		Oxfordian			
		Callovian			

The age of the Franciscan has long been a problem not only because of the scarcity of fossils but also because of additional complicating factors. No absolute criteria for the recognition of Franciscan lithology have been established, and geologists do not always agree on what is and what is not Franciscan. Further, because of structural complexities, even where fossils are found in an area generally agreed to be Franciscan the possibility may exist that the particular fossil-bearing rock is a foreign infolded or infaulted mass. An example of these difficulties is provided by the history of strata that crop out near Slate's Hot Springs, Lucia quadrangle, Monterey County. These rocks were first considered by Fairbanks (1894, p. 82; 1896; 1898) to be the basal beds of the pre-Cretaceous "Golden Gate Series" (= Franciscan Formation), but later work by Nomland and Schenck (1932) clearly established their Late Cretaceous age based on *Baculites* and *Inoceramus*. These rocks then were transferred by Taliaferro (1944, p. 507) to his non-Franciscan Asuncion Group, primarily on the basis of their Late Cretaceous age. Other rocks have had a similar history, in that they were first classed as Franciscan but then assigned to another stratigraphic unit when they were found to contain Cretaceous fossils.

San Francisco Area

The first authentic fossil obtained from rocks mapped by Lawson in the type area of the Franciscan Formation was found in a barge load of rock from Alcatraz Island, in San Francisco Bay, and was described as *Inoceramus ellioti* by Gabb (1869, p. 193, pl. 31, fig. 90a). Additional specimens of this species have not been found, and because of the fragmentary nature of the existing syntypic specimen (see Stewart, 1930, pl. 2, fig. 2), a positive age assignment cannot be made. The general form of this species, however, is comparable to other species of Cretaceous age. Subsequently other Cretaceous fossils have been found in the type area of the Franciscan; Schlocker, Bonilla, and Imlay (1954) reported the occurrence of *Douvilleiceras* cf. *D. mammillatum* (Schlotheim) from cliffs along the south side of the entrance to San Francisco Bay (fig. 22, no. 11), and Hertlein (1956) described a fragment of *Mantelliceras* sp. found on the beach on the north side (fig. 22, no. 10). These ammonites are

Figure 22. Map showing fossil localities in Franciscan.

Table 16. Franciscan Megafossil fossil localities.

Megafossil localities shown on map, fig. 22	Fossils present	Age	Location and remarks
1	*Buchia crassicollis*	Valanginian	Near Trinidad Head, Humboldt County. Fossils in block in shear zone.
2	*Buchia crassicollis*	Valanginian	West-central Yolla Bolly quad., sec. 11, T. 26 N., R. 10 W.
3	*Buchia piochii*	Tithonian	Covelo quad., near corners of secs. 15, 16, 21, 22, T. 24 N., R. 11 W. Feldspathic graywacke with pebbly mudstone, greenstone, and chert.
4	*Buchia crassicollis*	Valanginian	Northwestern part of Stonyford quad., 3 mi. S. 9° W. of Sheetiron Mtn., and ¼ mi. E. of Bowery flat. Fossils in limy shale and graywacke associated with greenstone and chert.
5	*Buchia piochii* and *B. crassicollis*	Tithonian and Valanginian	Southern part of Stonyford quad., sec. 25, T. 17 N., R. 7 W.
6	*Buchia piochii*	Tithonian	Two localities, one 4 mi. SW. of Skaggs Springs, the other in the NE. part of the Fort Ross 7½′ quad. Both these localities are in shear zones within Franciscan rocks. (photo. 67, figs. 6 and 8).
7	*Inoceramus labiatus* (Schlotheim)	Early Turonian	On Skaggs Springs road, Skaggs Springs 7½′ quad., sec. 24, T. 10 N., R. 11 W. (photo. 67, fig. 12).
8	*Inoceramus schmidti* Michael	Campanian	Found in two places; on Wolfe Grade, just S. of San Rafael, and in a quarry about 2 mi. SSE. of Novato. Fossils occur in thinly bedded sandstone and siltstone which may not be part of the Franciscan. (photo. 67, fig. 1).
9	*Buchia* sp.	Late Jurassic or Early Cretaceous	Small scraps of *Buchia* found by J. O. Berkland on U.S. Highway 101 just N. of San Rafael.
10	*Mantelliceras* sp.	Cenomanian	N. side of entrance to San Francisco Bay. In graywacke boulder occurring as float on beach.
11	*Douvilleiceras* cf. *D. mammillatum* (Schlothem)	Albian	S. side of entrance to San Francisco Bay. Found in massive graywacke. (photo. 67, figs. 2 and 3).
12	*Stereocidaris baileyi Nerinea* sp.	Late Cretaceous	New Almaden area, N. side of Baldy Ryan Canyon, one mi. ESE. of Fern Peak, Santa Teresa Hills quadrangle. Fossils found in oölitic limestone. (photo. 67, figs. 4 and 5).
13	*Icthyosaurus franciscanus* Camp. *I. californicus* Camp.	Late Jurassic or Early Cretaceous	Found in chert cobbles in Quaternary gravels at mouth of Corral Hollow Creek and near mouth of Del Puerto Canyon, E. side of Diablo Range.
14	*Aulacosphinctes* sp. juv. *Buchia piochii* (Gabb), and other fossils	Tithonian	Numerous localities NW. and E. of Stanley Mtn. Fossils occur in dark-gray shale interbedded with siliceous shale and greenstone, but assignment of these rocks to the Franciscan is questionable. See Easton and Imlay (1955, p. 2337, fig. 1), and Taliferro (1943a, p. 199, fig. 7) for locality data.

indicative of the Albian and Cenomanian Stages, respectively.

Thalmann (1942, 1943) first definitely established the Cretaceous age of what he regarded as the Calera Limestone Member south of the type locality, but he did not figure or describe any specimens. Cushman and Todd (1948) described a small fauna of Foraminifera obtained from tuffaceous beds intercalated in a small lens of Calera-like limestone that crops out near New Almaden in central Santa Clara County, and they suggested an Early Cretaceous age for this fossil assemblage. Glaessner (1949) revised some of their determinations and also postulated an Early Cretaceous (Albian) age. Küpper (1955) reexamined specimens from this same locality and reported the presence of the following species:

Globotruncana (*Rotalipora*) *globotruncanoides* Sigal
G. (*R.*) *apenninica apenninica* (Renz)
G. (*R.*) *evoluta* Sigal

G. (*Thalmanninella*) sp.
G. (*Rotundina*) *annalensis* (Sigal)
G. (*R.*) *stephani stephani* (Gandolfi)
G. (*R.*) *californica* (Cushman and Todd)
Planomalina buxtorfi (Gandolfi)
Globigerina sp.

This assemblage suggested to Küpper a Cenomanian, rather than an Albian age.

In 1961 Loeblich and Tappan (1961, p. 264) briefly discussed the fauna from this locality and listed the following planktonic species thought to be characteristic of a middle to late Cenomanian age:

Planomalina buxtorfi
Hedbergella trocoidea
Rotalipora greenhornensis
Praeglobotruncana stephani

The foraminiferal assemblage from near New Almaden is nearly the same age as a fauna obtained from the type Calera Limestone Member at Rockaway Beach by Church (1952, p. 70) who reported the following forms:

Globotruncana (*Rotalipora*) *appenninica typica* Gondolfi
Globotruncana stephani turbinata Reichel
Pseudoclavulina sp.
Pleurostomella sp.
Anomalina sp.
Pentalina sp.
Cibicides sp.
Gyroidina sp. cf. *G. depressa* (Alth.)
Schackoina cenomana (Schacko)

Franciscan foraminiferal limestone, either of the light-colored Calera type or the red Laytonville type, occurs in many places in the western part of the Franciscan outcrop area from the San Juan Bautista quadrangle in the south to the Scotia quadrangle in the north. Throughout this extent, Foraminifera generally are abundant in the limestone and all of the lenses studied so far seem to be approximately of the same age (see table 17). Thalmann (1943, p. 1827) reported on Cretaceous Foraminifera from a red limestone near Laytonville in northern California, and identified the following forms:

Globotruncana renzi Thalmann
Globigerina cretacea d'Orbigny
Gümbelina sp.
Bolivina sp.
Astacolus? sp.
Nodosaria sp.
Rotalia? sp.

The presence of *Globotruncana renzi* was thought by Thalmann to be indicative of a Turonian age.

Thin sections of limestone from other localities were examined briefly by Andrew Marianos of Humble Oil and Refining Co., and he reported the following fossils and age determinations (written communication, 1960):

Locality on figure 22	Foraminifera	Probable age
(1)	*Globotruncana helvetica*	Turonian
(3)	Abundant *Globigerina*(?)	?
(4)	No fauna listed	Late Cenomanian or early Turonian
(5)	*Globotruncana helvetica*	Turonian
(8)	*Praeglobotruncana stephani*	Cenomanian or Turonian
(9)	A few keeled forms and several with bulbous chambers	Possibly Cenomanian or Turonian
(10)	*Globotruncana helvetica* *Praeglobotruncana stephani*	Turonian
(11)	Abundant single-keeled form, indeterminable	Possibly late Cenomanian or early Turonian.

Megafossils are rare in the Franciscan limestone, but a nerineid gastropod and a large fragment of an echinoid (see photo 67) were found by Bailey in a lens of oölitic limestone in the New Almaden quadrangle (fig. 22, no. 12). The echinoid was described by H. Barraclough Fell of Victoria University, New Zealand, as a new species *Stereocidaris baileyi* Fell, which "is probably no older than Cenomanian . . . its closest congener is *S. merceyi* (Cotteau) of Senonian age" (Fell, 1962, p. 29). Elsewhere, corals of several different varieties, including hermatypic forms (oral communication, J. Wyatt Durham, 1961), bryozoa, Foraminifera, and molluscan fragments occur in small patches of limestone (photo 42).

The age of the limestones in the Franciscan has thus been established as Albian to Turonian on the basis of microfossils from many localities and "no older than Cenomanian" on the basis of a megafossil from a single locality.

Radiolaria are extremely abundant in Franciscan chert and siliceous shales, but, as yet, they have not received sufficient study to be of value in correlation. Hinde (1894) first figured several species of radiolaria, obtained from cherts from Angel Island and Buri Buri Ridge, on the San Francisco peninsula, including:

Cenosphaera sp.
Carposphaera sp.
Cenellipsis sp.
Ellipsidium sp.
Lithapium sp.
Tripocyclia sp.
Hagiastrum sp.
Dictyomitra sp.
Lithocampe sp.
Sethocapsa sp.

Table 17. Franciscan Foraminifera localities. (All in limestone of mid-Cretaceous age)

Foraminifera localities shown on figure 22	Location
1	Garberville quadrangle, 1½ miles east-southeast of Gilham Butte. Limestone block in sheared Franciscan.
2	Laytonville quadrangle, ½ mile and 2½ miles north of Laytonville, near U. S. Highway 101. Red limestone.
3	Ornbaun quadrangle, float beside road, 1½ miles northeast of Halvetian Gun Club. Red limestone.
4	Annapolis quadrangle, north side of Gualala River at WMCA camp. Thin lens of pink limestone associated with greenstone.
5	Cazadero quadrangle, on Gilman Ridge half a mile east-northeast of Luttrell Ranch. Limestone block in sheared Franciscan graywacke.
6	Point Reyes quadrangle, about 2 miles south of Olema. White limestone block in San Andreas fault zone.
7	San Mateo quadrangle, Rockaway quarry, 2 miles northeast of San Pedro Point. Calera Limestone Member of Franciscan Formation at type locality.
8	San Mateo quadrangle, 1,000 feet southwest of El Portal school in Burlingame. Limestone block in probable fault zone.
9	Palo Alto quadrangle, from Black Mountain and the Permanente Cement Co. quarry, 7.5 and 8 miles south of Stanford University.
10	Los Gatos quadrangle, road cut 0.23 mile west of Shannon road at a point 0.7 mile west of Guadalupe Creek. Limestone, calcareous tuff, greenstone, and graywacke. Fossils from this locality were described by Cushman and Todd (1948) and Kupper (1955).
11	San Juan Bautista quadrangle, on jeep trail on ridge 1.1 miles northwest of Castro Valley. Limestone lens interbedded with graywacke.

No definite age assignment was made by Hinde on the basis of these Radiolaria, but he noted that rocks of Jurassic and Cretaceous age in Europe contained the same genera, and therefore he suggested a similar age for the Franciscan. Radiolaria from shale beds interbedded with red chert near Belmont (San Mateo quadrangle) were described by Riedel and Schlocker (1956), who listed the following forms:

Conosphaera sp.
Cyrtellaria sp.
Cryptocephalus sp.
Dicolocapsa sp.
Tricolocampe sp.
Dictyomitra sp.

A Jurassic or Cretaceous age has also been postulated for this fauna.

No detailed or systematic study of pollen or spores from the Franciscan has been undertaken; however, Darrow (1951, p. 26) reports pollen belonging to families Betulaceae and Chenopodiceae was obtained from a sample of the Calera Limestone Member of the Franciscan Formation. According to Chaney (report of Darrow), this pollen could be no older than Late Cretaceous.

Northern Coast Ranges

Beyond the limits of the type area of the Franciscan Formation, graywacke and shale sequences can be assigned to the Franciscan with less assurance than can limestone and chert, as both of the latter are generally associated with volcanic rocks. Nevertheless, several fossil localities are known in clastic rocks interbedded with volcanic rocks, and these can be assigned to the Franciscan with reasonable certainty. North of San Francisco Bay, the presence of Upper Jurassic and lowermost Cretaceous Franciscan rocks is indicated in several places by the presence of *Buchia piochii* (Gabb) and *B. crassicollis* (Keyserling), respectively. Irwin (1957) listed several such localities, notably near Trinidad Head (Trinidad quadrangle), on Devils Hole Ridge (Yolla Bolly quadrangle), and near Bowery Flat (Stonyford quadrangle) (fig. 22, nos. 1, 2, and 4), all of which localities yielded *B. crassicollis*. Several other fossil occurrences have been found since Irwin's report. R. D. Brown found both *B. piochii* and *B. crassicollis* below a thick greenstone unit in the Stonyford quadrangle (fig. 22, no. 5) and Bailey found abundant specimens of *B. piochii* in sandstone accompanied by greenstone on Leech Lake Mountain in the Covelo quadrangle (fig. 22, no. 3).

That the eugeosynclinal rocks assigned to the Franciscan north of the type area also contain Upper Cretaceous clastic rocks is shown by a single specimen of *Inoceramus labiatus* (Schlotheim) collected by Bailey in the Skaggs quadrangle (Durham and Jones, 1959, p. 1716; also this report fig. 22, no. 7). This world-wide guide fossil to the lower Turonian (photo 67, fig. 12) is present in the Sacramento Valley at the base of the Venado Formation of Kirby (1943), and in the San Joaquin Valley in the lower part of the Panoche Group of Payne (1960).

Elsewhere within the northern Coast Ranges, still other localities have yielded fossils indicative of Late Jurassic and Early and Late Cretaceous ages (see fig. 22), but the relation of the rocks containing these fossils to surrounding Franciscan rocks is enigmatic. *Buchia piochii* occurs abundantly on a small peninsula on the southern shore of Lake Pillsbury in rocks which resemble shales of the Knoxville Formation, probably faulted into the dominantly Franciscan terrane. The same species also occurs in the Skaggs quadrangle, and in two places northwest of Ward Creek where the fossils occur in shear zones within Franciscan rocks (fig. 22, no. 6). *B. crassicollis* occurs in a non-Franciscan conglomerate exposed along Ward

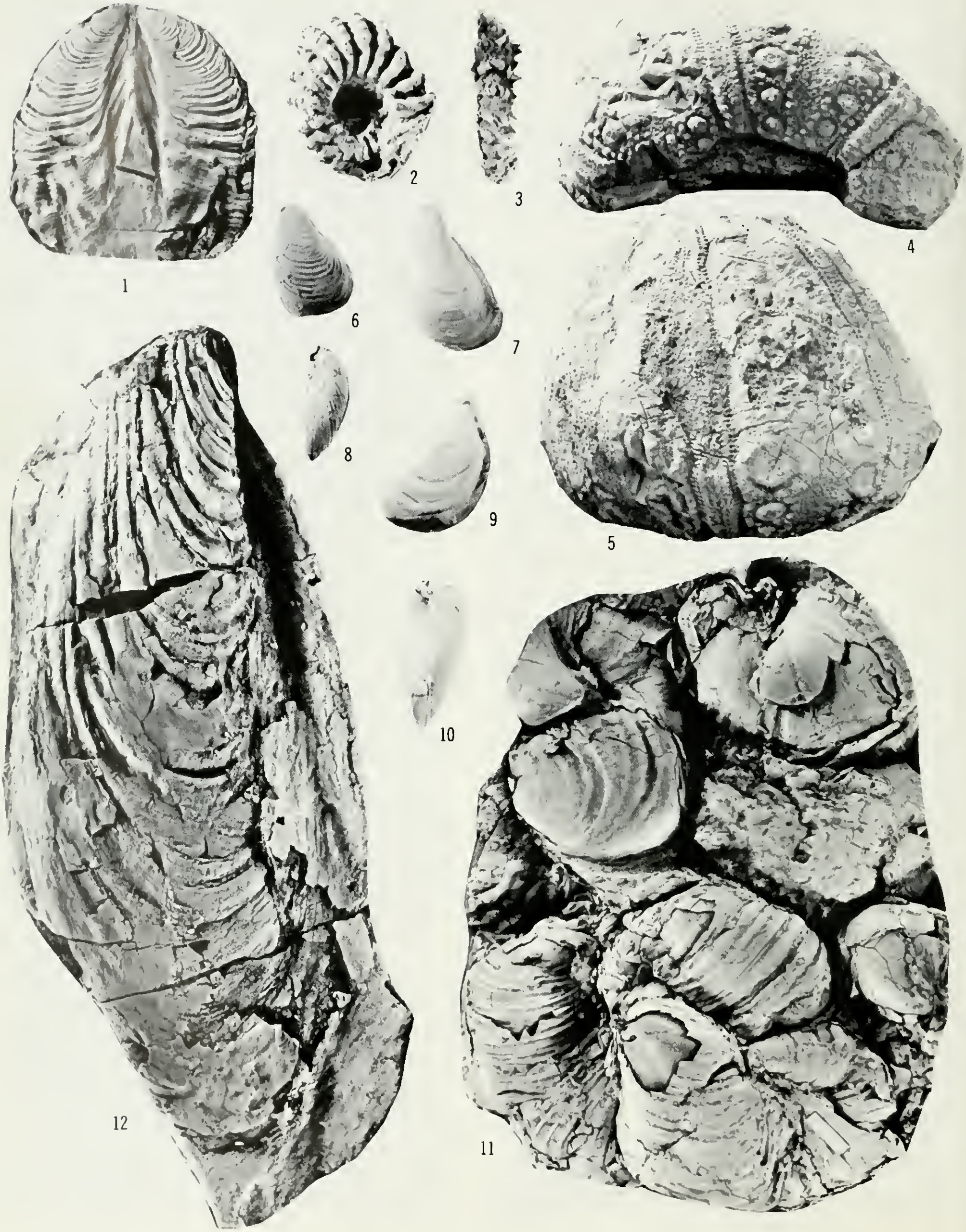

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Photo 67 (opposite). Fossils from the Franciscan and some related late Mesozoic rocks of the Coast Ranges.

Figure 1. *Inoceramus schmidti* Michael. Upper Cretaceous, Campanian. From thin-bedded graywacke and argillite in quarry 1 mile south of Novato, Petaluma quadrangle. These rocks were mapped by Lawson as Franciscan and are herein questionably included in the Franciscan.

Figures 2-3. *Douvilleiceras* cf. *D. mammillatum* (Schlotheim). Lower Cretaceous, Albian. From Franciscan graywacke on the south side of the Golden Gate, San Francisco. Rubber cast of specimen figured by Schlocker, Bonilla, and Imlay (1954).

Figures 4-5. *Stereocidaris baileyi* Fell. Upper Cretaceous. From Calera-type limestone in Longwall Canyon, Los Gatos quadrangle.

Figures 6-10. *Buchia piochii* (Gabb). Upper Jurassic, Tithonian. 6 and 8. Left valve of specimen from USGS Mesozoic loc. M269. From shear zone in Franciscan rocks in Skaggs quadrangle. 7, 9, and 10. Left and right valves of specimen from USGS Mesozoic loc. M438. From limestone nodule in Cretaceous conglomerate on Dry Creek, Skaggs quadrangle.

Figure 11. *Buchia crassicollis* (Keyserling). Lower Cretaceous, Valanginian. Slab containing many specimens from USGS Mezozoic loc. M439. From shale interbedded with conglomerate on Dry Creek that contained the reworked fossil listed above. These rocks are believed to be a part of the Great Valley sequence that is surrounded by Franciscan rocks, which are in part of Late Cretaceous age. Both *Buchia piochii* and *Buchia crassicollis* have been found in Franciscan rocks, but generally specimens are not as well preserved as those figured here.

Figure 12. *Inoceramus labiatus* (Schlotheim). Upper Cretaceous, Turonian. From interbedded Franciscan shale and graywacke in Skaggs quadrangle. This locality is about 1 mile from the rocks that yielded the older fossils shown as figures 7, 9, 10, and 11.

Creek in the Skaggs quadrangle, and it also has been found below thick conglomerates that crop out along Dry Creek several miles to the north (photo 67, fig. 1). This same species has been reported by Rose (written communication, 1960) to occur about 1½ miles southwest of Occidental in the Sebastopol quadrangle, and it has also been found north of Novato on the southeastern slopes of Burdell Mountain in the Petaluma quadrangle, and east of Novato just below the Novato Conglomerate. In all these localities, the rocks enclosing the fossils appear to be of miogeosynclinal nature, and thus we suspect they are foreign blocks tectonically brought into juxtaposition with the Franciscan rocks. In the Mount Tamalpais quadrangle small specimens of *B.* cf. *B. crassicollis* were found by James O. Berkland along U.S. Highway 101 about 1 mile north of San Rafael (fig. 22, no. 9) in rocks of Franciscan aspect, and a cobble of limestone bearing *B.* cf. *B. piochii* was found on Muir Beach west of Mount Tamalpais (Robert L. Rose, oral communication, 1960).

Inoceramus schmidti Michael, indicative of a Late Cretaceous (Campanian) age (photo 67, fig. 12) has been found in thinly bedded argillite at two localities, one west of San Rafael and one about a mile south of Novato (fig. 22, no. 8). These rocks were mapped as Franciscan by both Lawson (1914) and Weaver (1949b) and are included with the Franciscan on figure 1 of this report. However, as no volcanic rocks are known to occur with them, and their relation to the surrounding normal Franciscan rocks has not been determined, possibly they constitute younger infolded or infaulted masses of rocks unrelated to the Franciscan.

Southern Coast Ranges

The Franciscan rocks occurring south of the type area have yielded few fossils, and the age of these rocks has been established paleontologically in only a few places. Ichthyosaur snouts that were found in gravel deposits along the east side of the Diablo Range (fig. 22, no. 13) and described by Camp (1942) as *Ichthyosaurus franciscanus* are of either Late Jurassic or Early Cretaceous age (Camp, 1942, p. 370). In the Stanley Mountain area (Nipomo and Branch Mountain quadrangles) east of San Luis Obispo (fig. 22, no. 14), Taliaferro (1943a, p. 197-199) and Easton and Imlay (1955) have recorded Upper Jurassic fossils said to have been obtained from Franciscan rocks. According to Taliaferro (1943a, p. 198), "* * * in the Nipomo and Branch Mountain quadrangles north of the Cuyama River, there is a clear and unmistakable example of beds with typical Franciscan lithologic character but which contain fossils supposed to be characteristic of the Knoxville as exposed along the west side of the Sacramento Valley." These beds of supposed Franciscan character consist of black siltstone and shale which contains thin lenses and nodules of fossiliferous limestone, together with a thick sequence of volcanic rocks and associated chert and laminated siliceous shale. The following fossils were found in these beds northwest and southwest of Stanley Mountain by Taliaferro and identified by Crickmay (Taliaferro, 1943a, p. 198).

Protothurmannia rezanoffiana Crickmay
Berriasella cf. *B. calisto* (d'Orbigny)
Substeuroceras sp.
Crioceras sp.
Bochianites sp.
Phylloceras sp.
Lytoceras sp.
Pachyteuthis? sp.
Aucella terebratuloides Lahusen

From the same lithologic unit, but from localities several miles to the east of Taliaferro's localities, Easton and Imlay (1955, p. 2339) list the following forms, among others:

Aulacosphinctes? sp. juv.
Goniocylindrites? sp.
Amberleya? dilleri Stanton
Turbo? sp.
Procerithium paskentaensis (Stanton)
Aucella piochii (Gabb)

These two faunal assemblages provide an adequate basis for a Late Jurassic age for the Stanley Mountain rocks, but the relation of these fossiliferous rocks to the surrounding Franciscan rocks remains enigmatic. The Franciscan in the adjacent Cuyama River gorge consists mainly of graywacke, greenstone, and metamorphic rocks, all of which are structurally much deformed. These rocks apparently lack fossils, and they probably were deposited in a different environment and have a different geologic history than have the Upper Jurassic fossiliferous shales. Because of these differences it seems to be a gross oversimplification to lump both units as Franciscan simply because of the presence of greenstone and chert in each. It appears possible that the Upper Jurassic fossiliferous beds unconformably overlie the surrounding Franciscan, but additional geologic mapping is required to establish their relations.

In summary, the parts of the Franciscan that contain fossils can be assigned to ages ranging from Late Jurassic (Tithonian) to Late Cretaceous (Turonian) with certainty, and perhaps may include rocks of Campanian age. Upper Jurassic and Lower Cretaceous megafossils are uncommon, but, except for localities in shear zones west of Healdsburg, they have been found only in the eastern part of the outcrop belt between the north end of the Diablo Range and Trinidad Head. Upper Cretaceous megafossils and microfossils, which are more common, are confined to a western belt extending from the San Jaun Bautista quadrangle northward to the Garberville quadrangle. No reliable paleontologic data are available for the Franciscan west of the Nacimiento fault, although fossils of undoubted Late Jurassic age found in the Stanley Mountain area

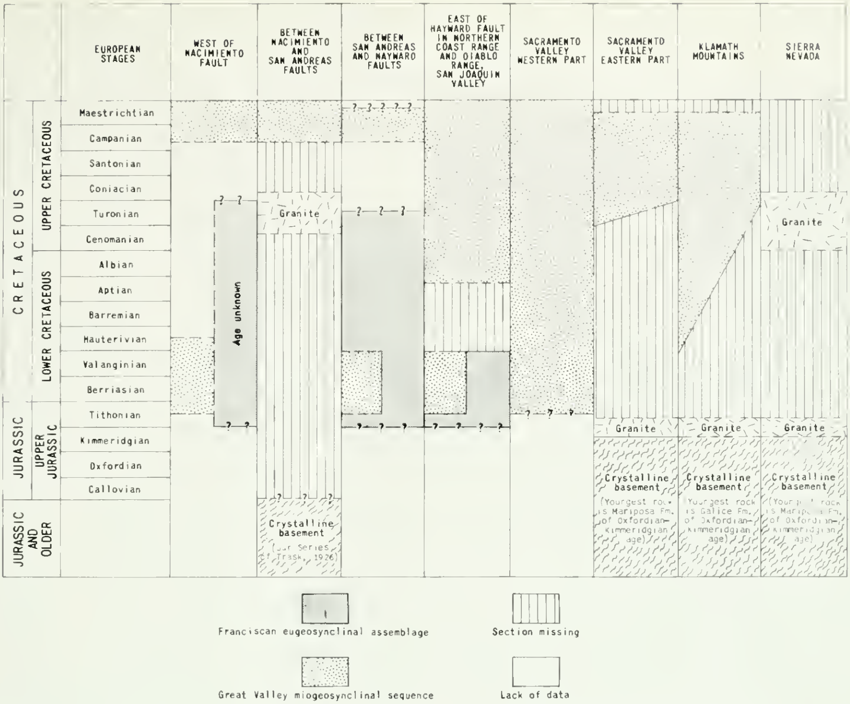


Figure 23. Correlation of upper Mesozoic rocks of the Coast Ranges, Great Valley, Klamath Mountains, and Sierra Nevada.

are regarded by some as occurring in rocks that they regard as Franciscan.

COEVAL MIOGEOSYNCLINAL ROCKS OF THE GREAT VALLEY AND COAST RANGES

The recognition of Lower and Upper Cretaceous fossils in Franciscan rocks made untenable the widely accepted pre-Knoxville age for all of the Franciscan Formation, and it also brought about the recognition (Irwin, 1957) of the fact that in western California there are two different thick sequences of rocks of Late Jurassic to Late Cretaceous age (fig. 23). One of these is the eugeosynclinal Franciscan; the other is a miogeosynclinal assemblage consisting chiefly of sedimentary rocks whose character indicates deposition on the continental shelf and slope. As the latter sequence is thickest and best exposed in the western part of the Great Valley, it is herein referred to as the Great Valley sequence, though it is not limited to this valley. Our subsequent discussions of the environment and origin of the Franciscan eugeosynclinal assemblage necessarily involves a consideration of the miogeosynclinal Great Valley sequence, so as background for the reader a brief sketch of the character and distribution of these rocks is provided in the following paragraphs.

Miogeosynclinal rocks of the Great Valley sequence have an aggregate thickness of 40,000 feet or more, with the maximum thickness occurring along the western margin of the valley. They are predominantly clastic and comprise an enormous volume of sandstone, conglomerate, and shale. Carbonate rocks are rare and consist mainly of thin lenticular beds and concretionary masses. Other chemically deposited rocks are absent, except for minor amounts of chert locally present in the lowest part of the sequence. This miogeosynclinal sequence differs in several ways from the partly coeval Franciscan eugeosynclinal rocks, and these differences are summarized in table 18. In brief, the Great Valley sequence differs from the Franciscan in nearly lacking greenstone and associated limestone and chert deposits, in having a higher proportion of fine-grained, shaly rocks, in having sandstone beds which are generally more uniformly and more thinly bedded, and in having a greater percentage of conglomerate, many more fossils (pl. 2), and much less structural deformity.

The miogeosynclinal rocks have received their most intensive study along the western margin of the Great

Table 18. Comparison of the Franciscan eugeosynclinal assemblage and the miogeosynclinal Great Valley sequence.

	Franciscan Eugeosynclinal	Great Valley sequence Miogeosynclinal
LITHOLOGY Sandstone	Graywacke, predominant, both feldspathic and volcanic varieties throughout. Chlorite cement predominates.	Graywacke, predominant in only parts of section, both feldspathic and volcanic in lower ⅔ of section, arkosic sandstone more abundant in upper ⅓. Chlorite, clay, or locally calcite cement.
Shale	Large proportion of fine mineral grains, micro-graywacke. Minor amount, and few sections predominantly shale.	Abundant, and locally forming more than half of thick section. Apparently higher quantity of clay minerals in shale and mudstone.
Conglomerate	Rare, generally in small lenses.	Generally present, and locally in very thick lenses.
Volcanic rocks and chert	Common in most areas.	Absent except in lower part of the Knoxville Formation.
Limestone	Associated with volcanic rocks.	Concretions and thin calcareous lenses common in shale sequences.
Metamorphic rocks	Glaucophane schist, jadetized graywacke, and others widespread.	Some zeolites in lowest part.
Serpentine	Widespread intrusives; sedimentary serpentine unknown.	Intrusives only in lower part of the Knoxville Formation; sedimentary serpentine locally in Lower Cretaceous rocks.
THICKNESS	50,000′+	40,000′
SEDIMENTARY FEATURES Bedding	Highly variable; beds ranging in thickness from less than an inch to more than a few tens of feet.	Thinly bedded, rhythmic alternations of sandstone and shale common, with more massive sandstone lenses interbedded. Beds generally have great continuity.
Current features	Virtually unknown in most areas; present east of Mount Hamilton.	Channeling and cut-and-fill structures in upper part of sequence. Ripple marks rare.
Slump features	Unknown.	Slump structures and convolute bedding common.
Turbidity current features	Graded bedding present in only a few areas. Sole markings very rare.	Graded beds and sole markings common in Sacramento Valley.
FOSSILS	Megafossils very rare; microfossils common in chert and limestone, rare elsewhere. Organic tracks and trails virtually unknown.	Megafossils locally abundant; microfossils common in Cretaceous rocks. Organic tracks and trails common.
DEFORMATION	Highly compacted, broken and sheared; overall structure complex but unknown in detail.	Moderately to slightly compacted, some faults with minor displacement, open folds.
DEPOSITIONAL ENVIRONMENT	Marine, probably deep water and dominantly bathyal; deposition by turbidity currents and fluxoturbidity currents.	Marine, upper neritic on east side of Sacramento-San Joaquin Valley grading to deep water on west side for much of the post-*Buchia*-bearing part. Deposition of eastern rocks by traction currents and western rocks in part by turbidity currents.

Valley, and here geologic mapping has advanced to the point where the general distribution of lithologic types and their age relations are fairly well known. As yet, however, no all-inclusive stratigraphic nomenclature has been developed, chiefly because rapid lithic changes along strike prohibit the widespread application of formational names. In the authors' opinion, such stratigraphic names as the Knoxville Formation, Shasta Series, and Chico Formation or Group (fig. 1), which have been widely applied both in the valley and throughout California, are based mainly on faunal, rather than on lithologic criteria; they are not acceptable rock-stratigraphic units. The Shasta Series and Chico Group are synonymous with Lower and Upper Cretaceous and are not used in this report. The Knoxville "Formation" refers to Late Jurassic *Buchia piochii* beds of the Coast Ranges.

Upper Jurassic (Knoxville) Rocks

Sacramento Valley. The name "Knoxville Beds" was first applied by White (1885, p. 19) to *Buchia* (= *Aucella*)-bearing beds of the Knoxville mercury district in the Morgan Valley quadrangle. Later studies, mainly by Anderson in the Sacramento Valley (1902; 1933a, b, c; 1945), resulted in restriction of the

Photo 68. Hogback ridges formed of rocks of the Great Valley sequence along the west edge of the Sacramento Valley as seen from the Coast Ranges to the west. Rocks in the foreground are Franciscan phyllite and serpentine.

name Knoxville to the lower, *B. piochii*-bearing portion, of presumed Late Jurassic (Tithonian) age, and the application of the name "Paskenta" to beds of the upper, *B. crassicollis*-bearing portion of Early Cretaceous age. This subdivision was based strictly on faunal differences, and proper recognition of either of these units depends on faunal criteria rather than on lithology.

Upper Jurassic rocks of the Sacramento Valley (fig. 24, 2) aggregate nearly 16,000 feet of shale, thin-bedded sandstone, massive, lenticular conglomerate, and, locally, pebbly mudstone (Anderson, 1933a, pl. 3; Crowell, 1957, p. 995-998). The lower part of the section in some places contains volcanic flows, tuff beds, and chert (Taliaferro, 1943a, p. 210; Lawton, 1956, p. 56; R. D. Brown, oral communication, 1960); these are well developed in the Stonyford and Wilbur Springs quadrangles. The upper 4,000 to 5,000 feet of Knoxville strata are abundantly fossiliferous and contain many specimens of *Buchia piochii* (Gabb) and related aucellan forms, as well as several species of belemnites, *Inoceramus*, and ammonites; the lower part is much less fossiliferous. The fossil assemblage is indicative of a fairly shallow-water marine environment.

In the Wilbur Springs and Morgan Valley quadrangles, Lawton (1956) mapped over 8,500 feet of Upper Jurassic sedimentary rocks consisting mainly of shale and mudstone with minor amounts of sandstone and conglomerate. The upper several thousand feet of beds are shale with a minor amount of sandstone (sandstone-shale ratio about 0.25) and numerous fossiliferous limestone concretions and limestone lentils up to 10 feet thick and several hundred feet long. In the middle and lower parts of the section sandstone is more abundant (sandstone-shale ratio near 1), and it occurs rhythmically interbedded with shale. The lower 1,500 to 2,000 feet consist of interbedded pillow basalts, massive basalts, basalt breccias, graywacke sandstone, limey shale, and minor amounts of chert and limestone.

Conglomerate is not abundant in the Upper Jurassic rocks near Wilbur Springs, but minor amounts occur in the lower part of the section. For the most part, these conglomerate lentils contain pebbles of chert and

Photo 69. Aerial view to the north-northeast from a point over the Abbott mercury mine, Wilbur Springs quadrangle, showing hogbacks formed by the upturned beds of the Great Valley sequence. Wilbur Springs is in canyon in the foreground near the right edge of the photograph; valley in central part is Bear Valley, while Sacramento Valley is in the distance. Farthest ridge extending from right edge only half way across picture is made up of Upper Cretaceous strata; smaller ridges from there to Bear Valley are Lower Cretaceous rocks; and between Bear Valley and brush covered ridge in center foreground is Upper Jurassic (Knoxville) rock. Brush covered ridge is serpentine and Franciscan rocks in the core of an anticline, with light areas in foreground being Great Valley sequence rocks on the near flank of the fold.

dark volcanic porphyries, but in at least one locality granitic debris is abundant.

Upper Jurassic sandstones are highly variable in composition, but all tend to be poorly sorted and to contain angular grains. Quartz content reported by Lawton ranges from 10 to 50 percent; feldspar averages 20 to 25 percent, and lithic fragments, including chert, range from 10 to about 40 percent.

Source areas for Knoxville sediments have not been positively identified, but presumably the bulk of the sediments was derived from the Sierra Nevada to the east and the Klamath Mountains to the north. Study of current-produced sedimentary structures in the Salt Creek-Grindstone Creek area (Elk Creek quadrangle) gives support to a Klamath source, as these structures show that currents came from a quadrant between north-northeast and north-northwest (Crowell, 1957, p. 995). No evidence is available to indicate that an important source area lay to the west of the Sacramento Valley. The northern limit of Upper Jurassic rocks is not known positively, but no definite Jurassic fossils have been found in the Great Valley sequence north of the north fork of Elder Creek in the Colyear Springs quadrangle.

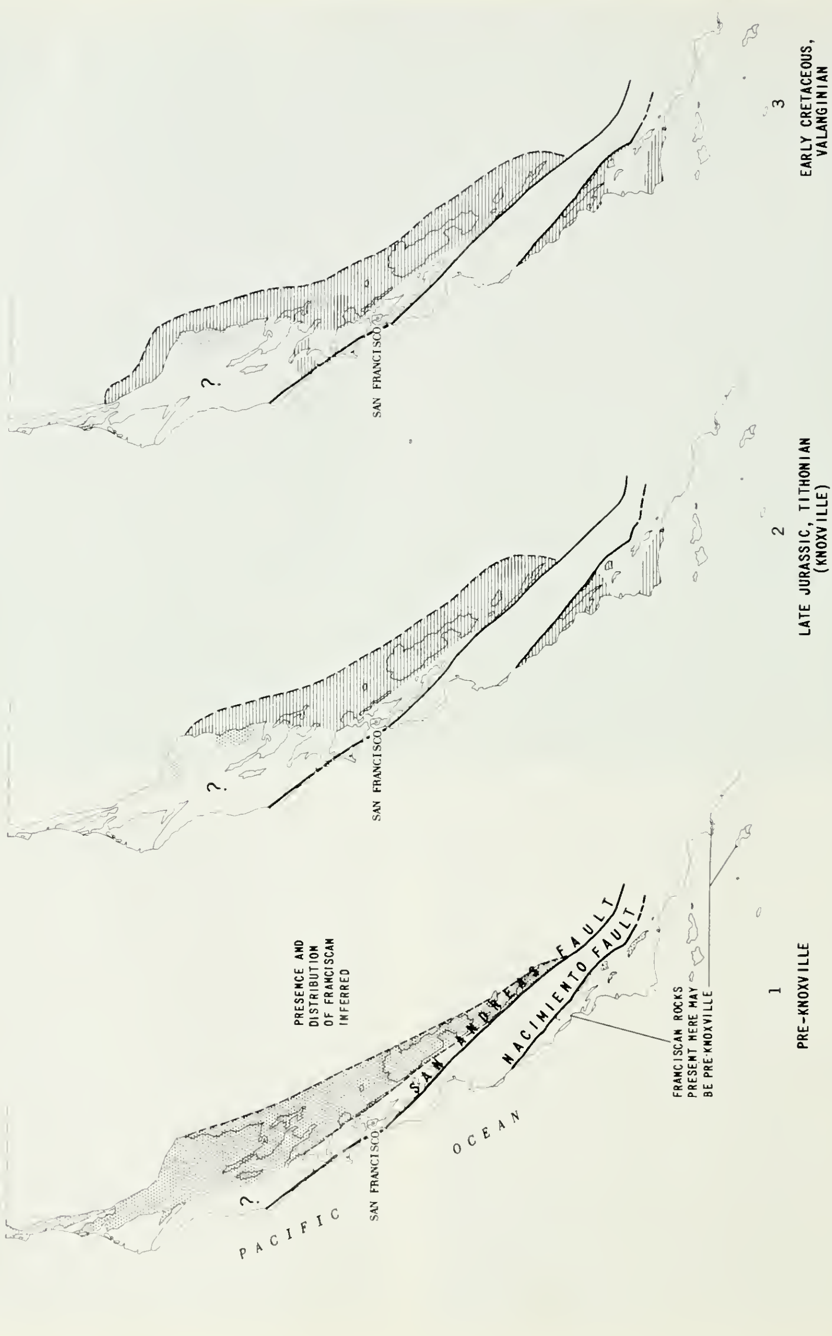
San Joaquin Valley. Buchia piochii-bearing sedimentary rocks are locally present in the San Joaquin Valley and are usually referred to as the Knoxville Formation. At no place within this area, however, do these beds approach the thickness found to the north in the Sacramento Valley. In the vicinity of Mount Diablo, Taff (1935, p. 1086-1087) reports the presence of about 2,000 feet of "dark clay and limey shales with variable lenticular strata of limestone and concretions of lime, sandy lime and ferruginous clay." These beds are overlain by or include an unknown, but probably small, thickness of shale and sandstone which contains *B. crassicollis*. Farther south in the Tesla quadrangle,

Photo 70. Thin-bedded graywacke and shale in upper part of Venado Formation (Late Cretaceous, Turonian) near Monticello Dam on State Highway 128, Capay quadrangle. Hat in lower left gives scale.

Dana Clark collected several specimens of *B. piochii* from a thin sliver of Upper Jurassic rocks in fault contact with the Franciscan south of Corral Hollow (U.S.G.S. Mes. loc. M1014). In the Pacheco Pass quadrangle, Fred Schilling and others have collected *B. piochii* as well as *B. crassicollis* from a 300-foot thick shale unit overlying, or in fault contact with, Franciscan volcanic and metamorphic rocks, and which in turn is overlain by massive conglomerates of Late Cretaceous age (Schilling, oral communication, 1960). Similar occurrences of a few hundred feet of *Buchia*-bearing sandstone and shale are known in the Priest Valley quadrangle west of Coalinga, in the Panoche quadrangle south of Panoche Pass (Enos, 1963), and in the Orchard Peak area, 20 miles southeast of Parkfield (Marsh, 1960). In the latter place, the Upper Jurassic and Lower Cretaceous fossils are intricately mixed with Upper Cretaceous fossils, so their stratigraphic significance is as yet unknown.

San Francisco Bay area. A narrow belt of Upper Jurassic rocks forms part of the foothills along the east side of the San Francisco Bay from Berkeley to south of San Jose. The dominant lithic types consist of thin-bedded gray shale and siltstone with minor amounts of sandstone and conglomerate. The total thickness is not known, but in the Hayward quadrangle, Robinson (1956) reports a lower sandstone-shale-conglomerate sequence 500 to 1,000 feet thick that grades upward into a predominantly shale sequence 1,500 to 2,500 feet thick. This shale unit also contains thin sandstone beds and abundant, loaf-shaped, fossiliferous lentils of brownish-gray fine-grained limestone. Farther south in the Mount Hamilton quadrangle, Crittenden (1951) reports an unknown thickness of dark-gray, thin-bedded fossiliferous shale which contains a sill of altered andesite.

In several places, notably in Berkeley and in the Hayward quadrangle, these Upper Jurassic rocks are reported to rest unconformably on more deformed volcanic rocks assigned to the Franciscan (Robinson, 1956). For the most part, these volcanic rocks consist of keratophyre and quartz keratophyre and probably are correlative with the volcanics found along the east


3
EARLY CRETACEOUS, VALANGINIAN
SAN FRANCISCO
?
2
LATE JURASSIC, TITHONIAN (KNOXVILLE)
SAN FRANCISCO
?
1
PRE-KNOXVILLE
PRESENCE AND DISTRIBUTION OF FRANCISCAN INFERRED
SAN ANDREAS FAULT
NACIMIENTO FAULT
FRANCISCAN ROCKS PRESENT HERE MAY BE PRE-KNOXVILLE
SAN FRANCISCO
?
PACIFIC
OCEAN

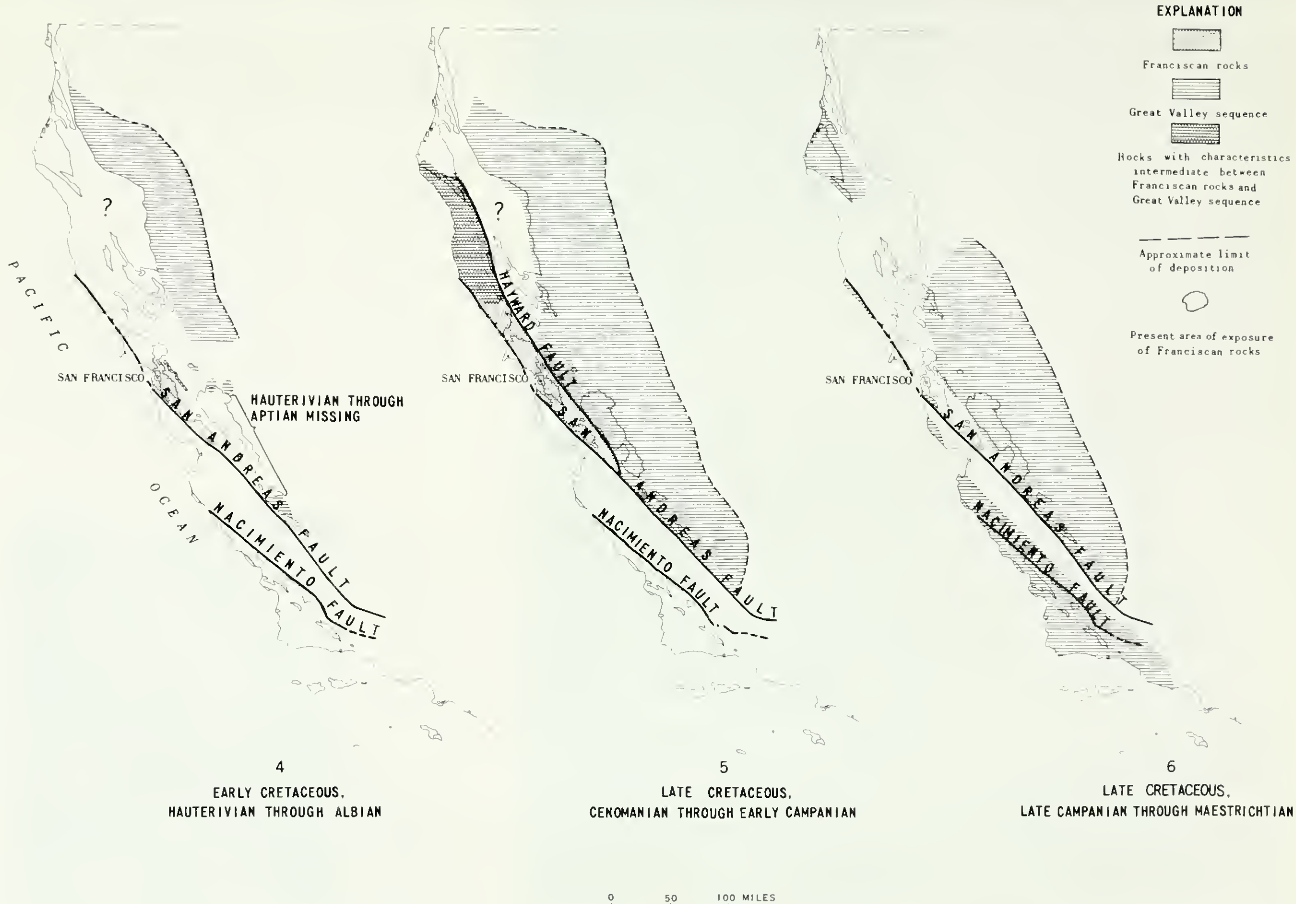


Figure 24. Maps showing areas known or inferred to be underlain by eugeosynclinal Franciscan rocks and miogeocynclinal rocks of the Great Valley sequence deposited during different intervals: (1.) Pre-Knoxville; (2.) Late Jurassic (Tithanian); (3.) Early Cretaceous (Valanginian); (4.) Early Cretaceous (Hauterivian through Albian); (5.) Late Cretaceous (Cenomanian through lower Campanian); (6.) Late Cretaceous (upper Campanian through Maestrichtian).

Photo 71. Eastward dipping Knoxville shales, on Stonyford-Elk Creek road, three miles north of Stonyford, in Stonyford quadrangle.

side of the Diablo Range in Del Puerto Canyon (Maddock, 1955) and near Panoche Pass (Enos, 1963).

Upper Jurassic rocks, indicated by the presence of *Buchia piochii*, have been reported from Stevens Creek in the Palo Alto quadrangle (Branner, Newsom, and Arnold, 1909, p. 3). We have been unable to rediscover this locality so cannot verify this reported occurrence.

Southern Coast Ranges. In the southern Coast Ranges, west of the Nacimiento fault, *Buchia piochii*-bearing beds are widely distributed from the Santa Ynez Mountains north of Santa Barbara, northwestward to the vicinity of San Simeon (San Simeon quadrangle). In the San Luis quadrangle, this species was obtained from dark shale and thin-bedded sandstone which was mapped by Fairbanks (1904) as the Toro Formation. This unit, which is over 3,000 feet thick, also contains *B. crassicollis* of Valanginian age, as was pointed out by Taliaferro (1944, p. 459) who abandoned the name Toro, regarded the Jurassic portion as part of the Franciscan-Knoxville Group, and named the Cretaceous portion the Marmolejo Formation.

Lower Cretaceous (Valanginian) Rocks

Distribution of shelf and slope deposits consisting of conglomerate, sandstone, and shale, characterized by the presence of *Buchia crassicollis* of Valanginian age, is essentially the same as that of the Upper Jurassic rocks (fig. 24, 3). In only one place, in the northwest portion of the Sacramento Valley, is the distribution of the two at variance. In this region, Jurassic fossils have been found only as far north as North Fork of Elder Creek in the Colyear Springs quadrangle. Upper Jurassic beds probably continue farther to the north, but at Beegum, in the Chanchelulla Peak quadrangle, rocks of Hauterivian age rest directly on metamorphic rocks of the Klamath Mountains (R. W. Imlay, written communication, 1961). The absence of *Buchia*-bearing beds at Beegum apparently represents a transgression upon the Klamath Mountains which carried the Early Cretaceous shorelines farther to the north than during Late Jurassic time.

Elsewhere within the Sacramento and San Joaquin Valleys, in the Diablo Range, in the Santa Lucia

Photo 72. Aerial view of strata of the Great Valley sequence as seen from a point above the Monticello dam, Lake Berryessa quadrangle. Peak circled is Berryessa Peak, and valley in upper right is Capay Valley. Nearly all of the rocks are part of an Upper Cretaceous section about 15,000 feet thick, ranging from the Venado Formation at Berryessa Peak to the Guinda Formation at extreme right and beneath Capay Valley.

Range, in the vicinity of San Francisco, and in the southern part of the northern Coast Ranges, the two species of *Buchia* commonly occur in normal stratigraphic sequence without an intervening change in lithology or an erosional surface to mark the Jurassic-Cretaceous boundary.

This similarity in distribution of *B. piochii*-bearing beds and *B. crassicollis*-bearing beds argues against an unconformity separating the two as has been proposed by Taliaferro (1944, p. 457), and Imlay (1959, fig. 36), and Popenoe, Imlay, and Murphy (1960, p. 1504-1505). The absence in California of a Berriasian and lower Valanginian fauna, such as is known from Alaska and parts of northern Canada, is puzzling, and lack of strata of these ages is one reasonable explanation. However, detailed mapping in the Sacramento Valley, by geologists of the U.S. Geological Survey and Stewart Chuber, has failed to show the presence of an unconformity or a lithologic break between beds containing *B. piochii* and those containing *B. crassicol-*

Photo 73. Flute casts and current lineation sole markings on lower surface of sandstone beds of the Sites Formation of Kirby, Great Valley sequence. Roadcut on south side of California State Highway 16 about 2½ miles north of Rumsey, Morgan Valley quadrangle. (*Photo by R. W. Ojakangas*).

lis (oral communication, R. D. Brown, Jr., 1961). Likewise, this work has failed to support the oft-quoted contention that these two species commonly occur together; in no instance was this found to be the case, but rather, these species were always separated by at least a few hundred feet of generally unfossiliferous strata. Perhaps this intervening barren section represents the "lost" Berriasian and lower Valanginian Stages but additional careful searching for fossils is necessary to assess such a view. Another possibility, that *B. piochii* ranges up in the lower part of the Cretaceous, cannot be discounted; undoubtedly Jurassic ammonites do occur with this species (see Anderson, 1945), but the stratigraphic distribution of these forms is poorly known.

A thick sequence of sedimentary rocks similar to those of the Great Valley sequence is exposed along Dry Creek west of Geyserville and extends southeast to the vicinity of Healdsburg. These rocks consist of a lower unit of fossiliferous shale overlain by a thick member of conglomerate and graywacke. Many specimens of *Buchia crassicollis* have been found in the shale as well as a few specimens of *B. piochii*, but the latter appear to have been reworked. Gealey (1951) termed the lower shale unit the Knoxville Formation of Late Jurassic age and assigned the conglomerate to the Cretaceous. Part of his evidence for a Late Jurassic age for the shale was based on an ammonite identified as *Berriasella storrisi* (Stanton), collected from a low ridge northeast of Fitch Mountain (Healdsburg quadrangle) and known elsewhere in rocks of Late Jurassic age. A plaster cast of this specimen was examined by R. W. Imlay (written communication to Jones, 1960) who stated that it seemed to be most similar to the Valanginian ammonite *Thurmanniceras stippi* (Anderson). Thus, it appears that most of these rocks along Dry Creek are of Cretaceous age.

A thick conglomerate similar to the conglomerate along Dry Creek is exposed on Ward Creek (Skaggs quadrangle) several miles to the south. *B. crassicollis* occurs near both the top and base, and this unit is correlative with the Dry Creek rocks.

The entire belt of sedimentary rocks exposed on Dry Creek differs markedly from the surrounding Franciscan rocks; this difference is seen particularly in the lack of greenstone, chert, serpentine, and metamorphic rocks, in the abundance of fossils, and in the less structurally deformed nature of the Dry Creek rocks. The Franciscan rocks and the Dry Creek rocks are in fault contact, and as it appears that at least some of the Franciscan is younger, it is difficult to explain the profound differences between the two adjacent assemblages.

Lower Cretaceous (Hauterivian to Albian) Rocks

Sacramento Valley. Rocks ranging in age from Hauterivian to late Albian are widely distributed along the western margin of the Sacramento Valley, but they do not occur along the eastern side (fig. 24, 4). In the Ono area, southwest of Redding, beds of these ages are abundantly fossiliferous and have received intensive study (Anderson, 1938; Murphy, 1956). Fossils are much less abundant in correlative rocks farther south; apparently this scarcity in fauna reflects deposition in water too deep to permit the development of a prolific shelly fauna.

In the Ono area, Murphy (1956) has mapped two Lower Cretaceous units: a lower unit, the Rector Formation, which consists of 20 to 400 feet of sandstone, conglomerate, and mudstone resting unconformably on igneous and metamorphic rocks of the Klamath Mountains; and an upper unit, the Ono Formation, which consists of about 4,200 feet of mudstone, siltstone, conglomerate, graywacke, and limestone. Mudstone and siltstone predominate, and graywacke and conglomerate are mainly confined to two large tongues in the lower and middle parts of the formation. Limestone occurs almost entirely as thin, lenticular beds and rounded or oval, concretionary masses.

Farther to the south, in the Wilbur Springs quadrangle, rocks of Hauterivian to Albian ages are much thicker, with an aggregate thickness of nearly 17,000 feet. These rocks also have here a higher percentage of sandstone and conglomerate (sandstone/shale ratio about 0.65, although this value is highly variable owing to pronounced local thinning of units and rapid facies changes). In many parts of the section, sandstone and shale are rhythmically interbedded, and the sandstone exhibits graded bedding, horizontal continuity of thin individual beds, and various types of sole markings suggestive of deposition by turbidity currents.

San Joaquin Valley and Diablo Range. Paleontologic evidence for the presence of rocks ranging in age from Hauterivian to Aptian in the San Joaquin Valley and Diablo Range is completely lacking, and it seems probable that beds of these ages either were not deposited or were removed by erosion prior to deposition of Upper Cretaceous rocks throughout most of this area. One possible exception may be in the Priest Valley quadrangle where a thick sequence of rocks overlies *Buchia*-bearing beds and in turn is overlain by Upper Cretaceous rocks, but no fossils have been found in this section to substantiate a Hauterivian to Aptian age.

Thin deposits of Albian age are present in a few places, notably in Curry Canyon on the southeast side of Mount Diablo, on the south side of Corral Hollow in the Tesla quadrangle, in the Hospital Canyon region in Carbona quadrangle, and, possibly, in the Coalinga area (S. W. Muller, oral communication, 1961). Reworked Albian ammonites occur in boulders in a conglomerate near the base of the Panoche Formation in the Panoche Valley quadrangle (Payne, 1960, fig. 5), but strata of this age are not known to crop out nearby. The Hospital Canyon locality is the best known and most fossiliferous of the San Joaquin Valley Albian deposits; these rocks consist of siltstone, shale, and interbedded concretionary, lenticular sand-

Photo 74. Aerial view of strata of the Great Valley sequence forming the Vaca Mountains, Lake Berryessa and Vaca quadrangles. Viewed looking south from a point about 4 miles north of the Monticello dam. Great Valley in background with Mt. Diablo beyond. Most of the rocks are Upper Cretaceous, with some lower Tertiary strata at upper left beyond narrow Vaca Valley.

stone which has yielded many specimens of ammonites, pelecypods, and woody debris. These rocks are in fault contact with Franciscan(?) volcanic rocks—and are overlain disconformably (oral communication, Marshall Maddock, 1961) by beds of Late Cretaceous (Coniacian) age. South of Hospital Canyon in the Mount Boardman quadrangle, Albian deposits are apparently missing as Maddock has collected Turonian fossils from shale only a few hundred feet above *Buchia*-bearing shale of Late Jurassic age. The Wisenor Formation of Briggs (1953a) which, in the Ortigalita Peak quadrangle, is supposed to lie unconformably below the Panoche Formation, also may be of Albian age, although no reliable paleontologic data is available.

Southern Coast Ranges. In the southern Coast Ranges, rocks of Hauterivian to Albian ages have not been positively identified, but rocks of Hauterivian age may be present. The Jack Creek Formation of Taliaferro (1944, p. 475, table 1), in the Adelaida and San Simeon quadrangles, was thought by him to be of Cenomanian and Turonian ages, but it is probably of Early Cretaceous age. The presence of belemnites in this formation is fairly good evidence for an Early Cretaceous age, as belemnites are completely unknown from Upper Cretaceous strata of California (Popenoe and others, 1960, p. 1520).

Upper Cretaceous Rocks

Sacramento Valley. Upper Cretaceous rocks cropping out along the west side of the Sacramento Valley comprise 15,000 feet or more of interbedded sandstone and shale and minor amounts of conglomerate (fig. 24, parts 5 and 6). Along the eastern side of the valley, Upper Cretaceous rocks are thinner, and from west to east successively younger rocks progressively overlap the basement rocks. At Chico Creek, on the eastern margin of the valley in the Paradise quadrangle, only a few thousand feet of sandstone, siltstone, and conglomerate, ranging in age from Coniacian to Campanian, are exposed (Saul, 1961, fig. between p. 21 and 22).

Photo 75. Pebbly mudstone with displaced blocks of interbedded sandstone and shale, at base of Venado Formation (Late Cretaceous, Turonian) near Monticello Dam on State Highway 128, Capay quadrangle.

The Upper Cretaceous rocks in the southwestern part of the Sacramento Valley were subdivided into the following six formational units by Kirby (1942, 1943): Venado, Yolo, Sites, Funks, Guinda, and Forbes Formations. Other formations, younger than those of Kirby, are known only in subsurface and have received informal names. Lawton (1956) has mapped in detail the Upper Cretaceous rocks of adjacent parts of the Wilbur Springs and Morgan Valley quadrangles, and most of the following information is taken from his work. The lowest Upper Cretaceous formation, of Cenomanian age, was named "Antelope Shale" by Taliaferro (1954), although this name was preoccupied. This unit consists of 4,500 to 5,200 feet of dark shale, siltstone, and sandstone, with shale greatly predominating. Sandstone occurs mainly in thin beds rhythmically interbedded with shale.

In the Ladoga quadrangle, west of Willows, Brown and Rich (1960) reported the presence of large lenses of slumped material near the base of Kirby's Venado Formation in rocks equivalent to the upper part of the "Antelope Shale." These lenses contain large blocks of reworked sedimentary rocks as well as boulders of quartz diorite. Albian fossils are also common in these lenses, and the presence of these fossils, several thousand feet stratigraphically above Cenomanian fossil localities, has resulted in various misconceptions concerning details of the local structure and stratigraphic sequence.

The overlying Venado Formation of Kirby (1943), of Turonian age, consists of 3,000 to 3,500 feet of interbedded sandstone, shale, siltstone, and thin lenses of conglomerate. Locally, sandstone comprises about 70 percent of the total thickness, but this percentage is variable due to rapid thickening and thinning of sandstone bodies as well as to facies changes along the strike.

The Yolo Formation of Kirby (1943) overlies the Venado and consists of 800 to 1,000 feet of shale and siltstone with occasional thin beds of sandstone. This unit is overlain by the Sites Formation of Kirby (1943), which comprises about 2,000 feet of massive- to well-bedded sandstone and rhythmically interbedded sandstone and shale. The Sites Formation is

Photo 76. Near-vertical sandstone dike cutting across gently dipping Late Cretaceous shale of the Great Valley sequence. North bank of Dry Creek about 5 miles west of Rosewood in the Ono quadrangle.

succeeded by the Funks Formation of Kirby (1942), which consists of 1,500 feet or more of shale with some siltstone and thin sandstone beds. The latter unit is followed by about 1,000 feet of massive- to well-bedded, fine- to medium-grained, buff-weathering sandstone termed the Guinda Formation of Kirby (1943). The section from the Sites to Guinda Formation ranges in age from Coniacian to probably early Campanian, but fossils from this sequence are rare and finely drawn paleontological subdivisions have not been recognized.

The highest exposed formation in the southwest part of the Sacramento Valley is the Forbes Formation. It consists of about 1,500 to 2,000 feet of gray shale, the lower portion of which contains numerous white-weathering limestone concretions that have yielded many specimens of ammonites and other fossils indicative of a Campanian age.

In contrast to the rocks found along the eastern side of the Sacramento Valley, which have yielded a prolific molluscan fauna, the rocks on the western side are sparsely fossiliferous, and with a few exceptions, have yielded only isolated and broken scraps. This lack of a well-developed indigenous fauna, together with fairly abundant sole markings, graded bedding, and other sedimentary features, suggests deposition of the west side rocks by the action of turbidity currents in relatively deep water. The well-developed fauna of the Forbes Formation appears to mark a period of shallower water, thus suggesting the gradual filling of the basin in Campanian time.

Source areas for the Upper Cretaceous rocks have not been identified positively, although the Sierra Nevada and Klamath Mountain blocks are the most likely source areas. No evidence is available to indicate a western source.

San Joaquin Valley and Diablo Range. Upper Cretaceous rocks are widespread throughout the Diablo Range and along the western side of the San Joaquin Valley where they have an aggregate thickness of between 25,000 and 33,000 feet. These rocks consist of sandstone, siltstone, shale, and conglomerate, with the dominant lithologic types being dark-gray clay shale

or mudstone with interbedded, thin to massive, gray, brown-weathering sandstone. In some places, beds of organic-rich shale, platy sandstone, or pebble and boulder conglomerate are abundant. Limestone is rare and for the most part occurs as small concretionary masses or thin, lenticular, nodular beds.

The strata of the San Joaquin Valley are customarily subdivided into two units, the Panoche and overlying Moreno Formations. Locally these units are recognized west of the San Joaquin Valley in the Diablo Range. In the Panoche Valley quadrangle, Payne (1960) assigned about 22,000 feet of shale and sandstone with several thick intercalated conglomerate lentils to his Panoche Group. The sandstone/shale ratio is approximately 1, or slightly greater. The sandstone is fine- to coarse-grained, with fine to medium sizes predominating; it is generally poorly sorted with angular grains. The quartz content varies from 20 to 60 percent, feldspar from 30 to 35 percent, and biotite averages 3 to 5 percent, although Briggs (1953b, p. 423) reports sandstone beds near the base of the Panoche in which abundant coarse biotite flakes constitute as much as 20 percent of the mineral fragments. Microgranular matrix, including clay, may constitute 25 percent of the total. Heavy minerals reported by Briggs from Upper Cretaceous sandstones are: hornblende, epidote, garnet, zircon, tourmaline, staurolite, rutile, sphene, and apatite. Rock fragments with chert, volcanic, and plutonic rocks most abundant are reported by Briggs from almost every specimen studied, and glauconite was found in a third of the specimens.

The overlying Moreno Formation consists of about 3,000 feet of interbedded chocolate-brown, maroon, light-brown, and creamy gray colored, organic-rich shale and fine-grained, gray, silty sandstone. The sand/shale ratio is about 0.12. Payne (1951) considered the upper portion of this formation to be of Paleocene age, and the contact between the Cretaceous and Tertiary to be gradational.

Lenses of conglomerate which locally attain a thickness of 1,000 feet or more and a length of several miles are particularly common in the Panoche Formation in the Pacheco Pass, Ortigalita Peak, and Panoche Valley quadrangles (Anderson and Pack, 1915, p. 43). The conglomerate is composed of pebbles and cobbles of various porphyritic and granitic rocks, as well as chert, quartzite, limestone, and sandstone. Clasts range in size from small pebbles to rounded cobbles and boulders 15 to 20 inches in diameter, and fragments up to 12 feet long have been reported (Anderson and Pack, 1915, p. 43). According to Anderson and Pack (1915, p. 43), "The great bulk of the pebbles are of a type of rock different from those now exposed in the center of the Diablo Range, and the location of the land mass from which they were derived is problematic." According to Briggs (1953a, p. 35) about 1 to 2 percent of the total Cretaceous sequence of the Ortigalita Peak quadrangle is conglomerate; the percentage in the Pacheco Pass quadrangle is appreciably greater.

Detailed mapping, particularly by Schilling (1962) in the Pacheco Pass quadrangle, has emphasized the striking lateral facies changes exhibited by these rocks. Thick, massive, sandstone bodies grade laterally into siltstone and shale, and thick lenses of conglomerate pass over a short distance into sandstone. Few lithologic units can be traced continuously from one end of a 15-minute quadrangle to another.

In many places along the west side of the San Joaquin Valley and in the Diablo Range, the Panoche Formation is in fault contact with the Franciscan, but locally the Panoche overlies, with apparent disconformity, *Buchia*-bearing shelf deposits of Late Jurassic and Early Cretaceous (Valanginian) age. In a few places, notably in and south of Hospital Canyon (Carbona quadrangle), rocks of Albian age are present below the Panoche. Undoubtedly, within the thick sequence of Upper Cretaceous rocks, other local unconformities, disconformities, and diastems are present, but detailed mapping has not progressed to the point where the significance of such structures can be evaluated.

Source areas for the vast amount of sediments deposited during Late Cretaceous time in the San Joaquin Valley and Diablo Range have not been positively identified, but certainly the Sierra Nevada area contributed a substantial, if not preponderant, amount. The concept of a western source for some of these sediments has been widely cited (Taliaferro, 1943b, p. 134; Briggs, 1953b, figs. 6 and 7), but positive evidence in support of this view is lacking. Briggs suggests that the quantity of volcanic and plutonic-metamorphic cobbles in conglomerates points to a western source, although why a Sierra Nevadan source is ruled out is not clear. Briggs also cited evidence from sedimentary structures, such as slump structures and cross-bedding, which he thought supported a western source, but data of this nature are still so fragmentary that little or no weight can be given to them. According to R. R. Compton (oral communication, 1961) no detritus definitely indicative of a western, Sur Series, source has yet been identified from the San Joaquin sequence.

Fairly cogent evidence in support of the concept that the Gabilan Range and "Cascadia" (Reed, 1933) did not shed sediments into a San Joaquin Valley sea is found in the Late Jurassic, Early Cretaceous (Valanginian), and Late Cretaceous rocks of the San Benito quadrangle mapped by Wilson (1943). Although some of these rocks lie only 2 or 3 miles east of the crystalline rocks of the Gabilan Range, from which they are separated by the San Andreas and related subsidiary faults, debris from the distinctive metamorphic rocks of the Sur Series in the Gabilan Range has not been identified in these sedimentary rocks. Thick conglomerates that would suggest proximity to a source area are scarce in the San Benito

area, although farther east in the San Joaquin Valley they are abundant. Likewise, the absence in the San Benito area of a prolific heavy-shelled, shallow-water molluscan fauna such as occurs in correlative beds in the Ortigalita Peak and Pacheco Pass quadrangles (the so-called "*Glycymeris reef*" beds) indicates that the water did not become shallow on approaching the Gabilan Range as was diagrammatically indicated by Briggs (1953b, fig. 7).

Southern Coast Ranges west of San Andreas fault. Upper Cretaceous rocks of the southern Coast Ranges west of the San Andreas fault are poorly known and have been studied in detail only in a few places; most of the maps available are at small scales or are out of date.

In the Santa Lucia Range, Taliaferro (1944) recognized two units, the Jack Creek Formation and the overlying Asuncion Group, both of which were thought to be of Late Cretaceous age, but separated by an unconformity that marked the so-called Santa Lucian orogeny. The Jack Creek Formation is probably of Early Cretaceous age and has been discussed previously. The Asuncion Group, however, is of latest Cretaceous age and is widely distributed. In places it rests on the eroded Santa Lucia quartz diorite and Sur Series (Reiche, 1937, p. 137; R. Compton, oral communication, 1961), and it also is mapped as lying on the Franciscan (Eckel and others, 1941, pl. 78). In the Lucia quadrangle Reiche (1937) reports between 3,000 and 4,800 feet of dark-gray to black mudstone interbedded with medium-to coarse-grained, feldspathic sandstone, and with as much as 1,300 feet of boulder conglomerate in the basal portion. Locally, massive breccias, with fragments up to 10 feet long, are present near the basal contact. Fossils are abundant in parts of the Asuncion, but no detailed collecting or paleontologic studies have been carried out. Judging from the fossils listed by Reiche (1937, p. 137) and Taliaferro (1944, p. 502), a probable age of late Campanian to Maestrichtian for these rocks is suggested. Significantly, the rudistid pelecypod *Coralliochama orcutti* White, which in Baja California is restricted to beds of probable early Maestrichtian age, is present in the Santa Lucia Range a short distance above the base of the Asuncion (R. Compton, oral communication, 1961). Likewise, Inocerami and *Baculites* from thin-bedded black siltstone at Slate's Hot Springs (Lucia quadrangle) are also suggestive of a late Campanian, or younger, age (Nomland and Schenck, 1932).

In the Transverse Ranges north and west of Santa Barbara, thick sequences of Cretaceous rocks are exposed, but paleontological data is not available to adequately date all of these rocks. Dibblee (1950) named the Espada Formation from exposures in the western part of Santa Barbara County. There, 4,000 to 6,800 feet of dark greenish-brown sandy shales have been tentatively assigned a Late Jurassic to Early Cretaceous age (Dibblee, 1950, p. 38, fig. 2), and the youngest fossil known from this unit is *Buchia crassicollis.* The Jalama Formation (Dibblee, 1950, p. 23-24) overlies the Espada Formation and comprises about 4,000 feet of clay, shale, and sandstone. Shallow-water, heavy-shelled molluscan fossils are abundant locally in this unit, and they suggest an age no older than Campanian.

Farther to the east, Page, Marks, and Walker (1951) recognized three Cretaceous formations, one of which crops out north of the Santa Ynez fault, and two of which crop out south of the fault. The strata north of the fault have not been formally named; these comprise 16,000 feet or more of dominantly dark-gray shale with thin sandy and calcareous interbeds. The age of this unit is not well established, but the fossils reported include both Upper Jurassic and Lower Cretaceous species of *Buchia* as well as *Coralliochama orcutti* and other fossils indicative of a Late Cretaceous (Campanian or younger) age. No paleontologic evidence is available to show the presence of beds intermediate in age between these two established ages, and it is possible that such beds are lacking. South of the Santa Ynez fault, Page, Marks, and Walker recognized the Debris Dam Sandstone comprising about 2,200 feet of interbedded sandstone, shale, and conglomerate, which locally contains an abundant molluscan fauna similar to that of the Jalama Formation. Overlying the Debris Dam is the thin Pendola Shale comprising 440 to 1,000 feet of dark-gray to greenish-gray shale; no diagnostic fossils are known from this unit.

Source areas for all of the Upper Cretaceous rocks of the southern Coast Ranges west of the San Andreas fault are not known, but undoubtedly the crystalline rocks of the Santa Lucia Range have furnished a predominant amount of sediment. No evidence to support a source farther west, as advocated by Taliaferro (1944, p. 488), is available.

The geologic history of the southern Coast Ranges west of the San Andreas fault is poorly understood, but some very perplexing problems are apparent. For example, neither the Franciscan nor the Upper Jurassic and Lower Cretaceous (Valanginian) rocks of the Great Valley sequence lying west of the Nacimiento fault zone are intruded by granite, and they show no effects of the mid-Cretaceous intrusion of the plutonic rocks of the Santa Lucia Range. This relation is exactly the same as that along the San Andreas fault where Jurassic and Cretaceous rocks likewise were unaffected by the granitic instrusions. Similarly, between the time of intrusion and the latter part of the Cretaceous, exceedingly rapid erosion must have removed enormous quantities of rock in order to expose the plutonic rocks, as rocks as old as Campanian rest on a surface eroded across Upper Cretaceous crystalline rocks. Inexplicably, no deposits formed from the removal of the noncrystalline overburden have been identified, either in the San Joaquin Valley or west of the Nacimiento fault (fig. 29). The absence of such deposits, as well as the lack of metamorphic

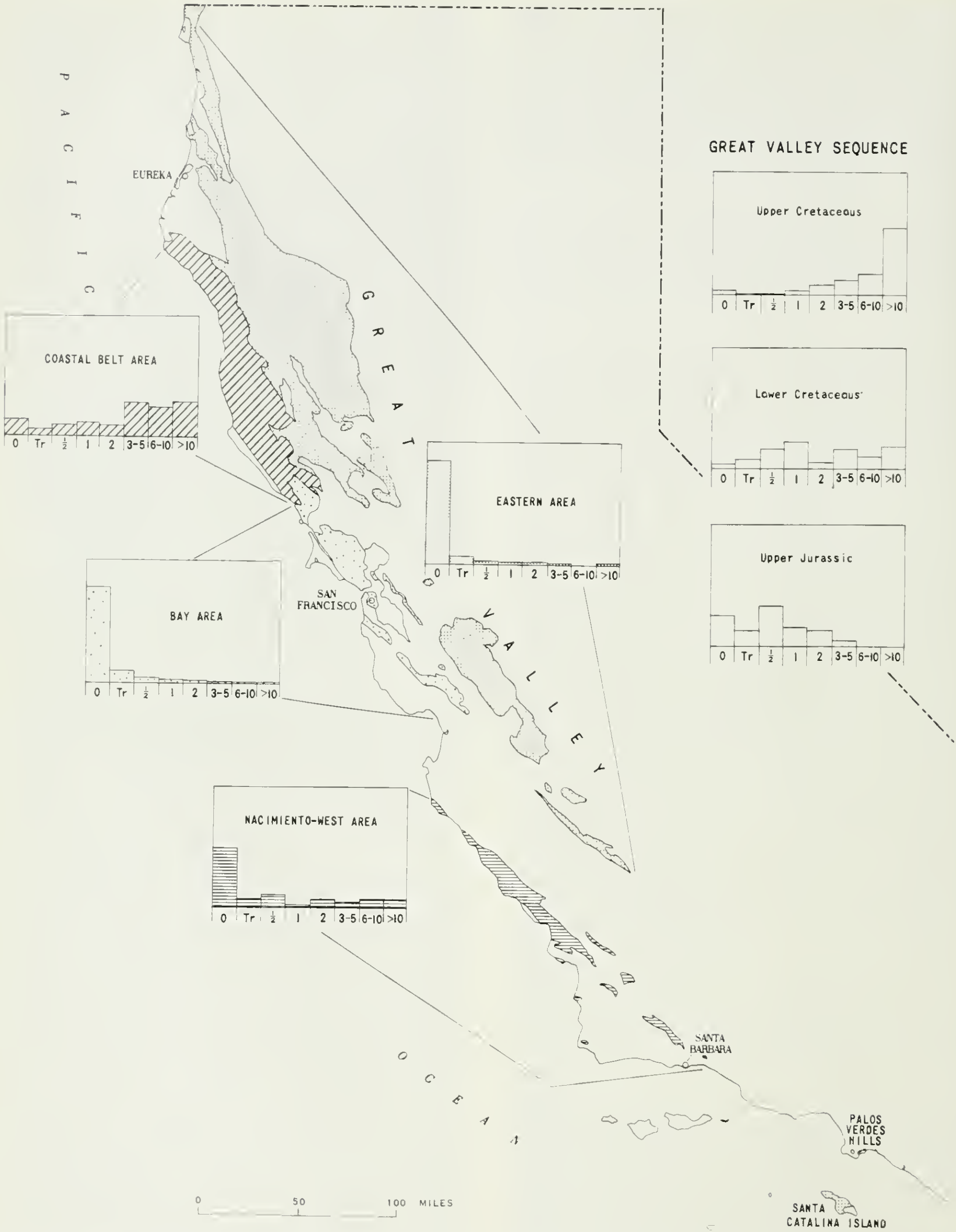


Figure 25. Map showing four geographic categories of Franciscan rocks. Histograms show K-feldspar distribution in Franciscan rocks of each category, and in rocks of the Great Valley sequence.

effects due to the mid-Cretaceous granitic intrusions, suggests that the Nacimiento-west block is structurally displaced and has been juxtaposed against the granitic block in Late Cretaceous or, more likely, in post-Cretaceous time. Similiarly, the lack of a thick clastic wedge extending from the Gabilan Range eastward into the San Joaquin Valley adds some weight to the concept that the granitic block has moved a great distance laterally along the San Andreas fault.

K-FELDSPAR CONTENT OF GRAYWACKES OF THE FRANCISCAN AND GREAT VALLEY SEQUENCE

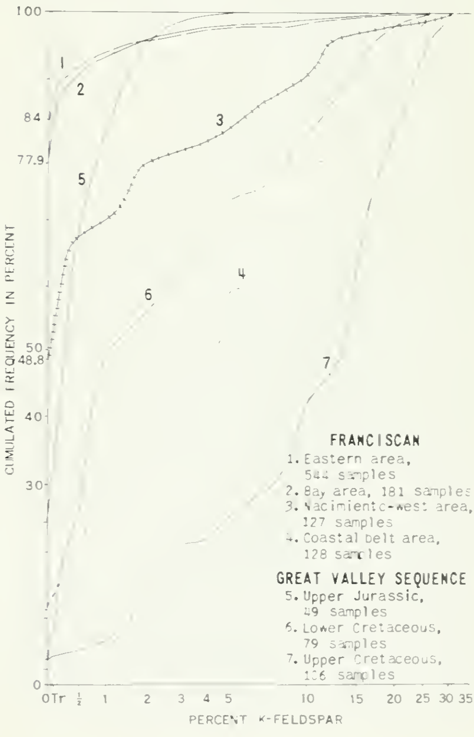
The graywackes of the Franciscan eugeosynclinal assemblage and the miogeosynclinal Great Valley sequence can be distinguished in most places with little difficulty by their lithology or lithic associations. However, in some areas, particularly where a block of graywacke is surrounded by faults so that its true lithic associates are unknown, the sedimentary characteristics of the graywacke may be inadequate to assign it with assurance to the proper major facies assemblage. In the hope of finding a positive mineralogic difference between the graywackes of the two assemblages, we have determined the K-feldspar content of many specimens collected from both assemblages throughout the Coast Ranges (pl. 2). The resulting data indicate that the K-feldspar content can be used in some areas as a positive means of separating graywackes of the two facies, but in other areas it does not provide a distinguishing criteria. However, because of an apparent systematic increase of K-feldspar with decreasing age, the K-feldspar content may locally provide a crude method for determining the probable age of unfossiliferous late Mesozoic strata in the Coast Ranges. The K-feldspar content also bears on the provenance of the two assemblages and places limits on concepts regarding their gradational relations.

Preliminary studies of the K-feldspar content of graywackes collected from the northern Coast Ranges and northern Great Valley were reported by Bailey and Irwin (1959), who found that most Franciscan graywackes contain little or no K-feldspar while the graywackes of the Great Valley increase in K-feldspar content with decreasing age of the strata. As the promising results of the preliminary studies indicated a need for more widespread sampling, in 1960 the equivalent strata of the southern Coast Ranges were sampled by Bailey, Irwin, and Jones, and additional samples were loaned us by other geologists. The method of testing graywackes for K-feldspar was described in detail previously (Bailey and Irwin, 1959). Briefly, this method consists of sawing a surface on the specimen, etching this surface by immersion in hydrofluoric acid, and treating the etched surface with a saturated solution of sodium cobaltinitrite. A bright yellow-orange stain of potassium cobaltinitrite forms on any grains of potassium feldspar that are present. The specimen is then viewed under a binocular microscope, and the percentage of potassium feldspar is estimated by comparison with a set of measured standard samples.

The samples of graywacke were obtained from all major areas of Franciscan rocks and adjacent areas of miogeosynclinal rocks of late Mesozoic age, as is shown on plate 2. The data regarding K-feldspar content was tabulated separately for the Upper Jurassic, Lower Cretaceous, and Upper Cretaceous units of the Great Valley sequence and for four geographic categories of the Franciscan. The four categories are the so-called eastern areas, Bay areas, Nacimineto-west areas, and coastal belt (fig. 25). Cumulative frequency distribution curves based on these tabulations are shown on figure 26.

The assignment of the samples to formational units was based chiefly on available geologic maps. The designations shown on the maps agreed in most cases with our concept as to what should be mapped as Franciscan and non-Franciscan, but it was apparent that the rocks in some areas had been misidentified. Thus, we were in the position of attempting to develop criteria for distinguishing among graywacke of various formations on the basis of samples that include some which

Figure 26. Cumulative frequency distribution curves for K-feldspar content of upper Mesozoic graywackes.



are misidentified. Others that were misidentified, but not obviously so, may also have been included. Most of the samples, however, are thought to be properly assigned, and it is the gross statistical result, rather than minor deviations resulting from "salting", that is considered to be significant.

The cumulative frequency curves (fig. 26) for the Franciscan of the eastern and Bay areas are much alike, but differ markedly from those of the coastal belt and Nacimiento-west areas. The curves for the eastern and Bay areas show that 84 and 77.9 percent, respectively, of the specimens of graywacke mapped as Franciscan in these areas contain no K-feldspar and that the rest range from a trace to 25 percent in K-feldspar content. By comparison, 48.8 and 11.3 percent of the specimens of the Nacimiento-west areas and coastal belt, respectively, contain no K-feldspar. Furthermore, the median graywacke of the Nacimiento-west areas and coastal belt contains K-feldspar, and specimens represented by the 75-percentile points contain considerable amounts, whereas corresponding specimens for the eastern and Bay areas contain no K-feldspar.

Although a trace or more of K-feldspar was found in a small percentage of the specimens of graywacke mapped as Franciscan in the eastern and Bay areas, some of these graywackes were noted, when collected in the field, as questionably Franciscan because of the character of their bedding or the apparent absence of greenstone and chert in the stratigraphic section. In the eastern area of Franciscan most of the K-feldspar-bearing graywackes are along the western side near the coastal belt, whereas specimens collected from broad areas of graywacke mapped as Franciscan in the eastern part of the eastern area are generally devoid of K-feldspar.

In general we have viewed most K-feldspar-bearing graywacke as dubiously Franciscan (Bailey and Irwin, 1959). Nevertheless, some of the Franciscan graywackes surely contain appreciable K-feldspar. This is most clearly demonstrated in southern Marin County where graywacke interbedded with greenstone and chert in a thick section of typical Franciscan lithology contains quantities of K-feldspar ranging from a trace to several percent. In the southern part of the San Francisco peninsula some of the graywacke associated with the Calera limestone, greenstone, and chert of the Franciscan formation, contains K-feldspar, although to the southeast along the same belt of limestone in the Morgan Hill and San Juan Bautista quadrangles, graywacke collected from apparently the same stratigraphic units contains no K-feldspar.

The rocks of the Great Valley sequence of Late Jurassic age are represented in the cumulative frequency distribution curve for K-feldspar content (fig. 26) by 49 specimens, most of which are from the Knoxville Formation on the west side of the northern Great Valley. The K-feldspar content of the specimens ranges from 0 to as much as 5 percent; the median is somewhat less than 0.5 percent.

The curve for the K-feldspar content of the Lower Cretaceous of the Great Valley sequence is represented by 79 specimens collected from the strata along the west side of the northern Great Valley and from patches of related strata in other parts of the Coast Ranges. The specimens range in K-feldspar content from 0 to as much as 25 percent; all of the specimens of the Lower Cretaceous along the west side of the northern Great Valley contained a trace or more K-feldspar. The median K-feldspar content is 1.1 percent.

The curve for the K-feldspar content of the Upper Cretaceous rocks of the Great Valley sequence is based on 106 specimens. The specimens were collected from strata commonly referred to as "Chico" along the west side of the northern Great Valley as well as elsewhere in the Coast Ranges and from the Yager Formation of Ogle (1953) and the Gualala Series of Weaver (1943). The K-feldspar content of these specimens of graywacke ranges from 0 to 30 percent; all from the northern Great Valley contained 0.5 percent or more K-feldspar. The median K-feldspar content of the specimens of the Upper Cretaceous is nearly 13 percent.

The foregoing values for the median K-feldspar content of the graywackes of the Franciscan and of the Upper Jurassic and Lower Cretaceous of the Great Valley sequence are nearly identical to the preliminary median values reported by Bailey and Irwin (1959). This close agreement exists even though the specimens used to determine the preliminary values were less than half as numerous and were collected from only a part of the northern Coast Ranges and northern Great Valley. Also, this agreement suggests that the source of the graywackes of the Franciscan and of the Upper Jurassic and Lower Cretaceous of the Great Valley sequence did not differ in regard to availability of K-feldspar from north to south along the length of the depositional area during any single period of sedimentation. On the other hand, the K-feldspar content of the graywacke of the Franciscan is different from east to west, with K-feldspar being rather generally present in the Franciscan only in some places along the west side of the Coast Ranges.

The additional sampling reported in this paper substantiates the original concept (Bailey and Irwin, 1959) that the K-feldspar content of the graywackes of the Great Valley sequence systematically increases with decreasing age of the three stratigraphic units. This relation pertains not only to the strata of the northern Great Valley but for the miogeosynclinal strata of similar age throughout the Coast Ranges. If the general source area of these strata was essentially the same geographically, as seems likely except perhaps for some of the latest Cretaceous, the change in K-feldspar content of the strata must reflect a gradual change with time in the bulk rock, and therefore mineral, composition of the source area. Thus the measure of the K-feldspar content should serve as a rude geologic calendar for all strata derived from that source

during the span of time represented by strata of the Great Valley sequence.

The advisability of extending this observation to apply to the eugeosynclinal Franciscan rocks is subject to question, but worth considering. If one applies this observation to the Franciscan, one must assume that the source of the Franciscan graywacke was essentially the same geographically as the source of the Great Valley sequence. Assuming this, and based only on the K-feldspar content of the sediments, the Franciscan would seem to have been deposited during more than one period of geologic time or continuously through much of Late Jurassic to Late Cretaceous time. The Franciscan graywacke in the eastern part of the Coast Ranges generally contains no K-feldspar and thus would be older than the Upper Jurassic (Knoxville) rocks of the Great Valley sequence. Some of the Franciscan graywackes in the western part of the Coast Ranges contain appreciable K-feldspar and therefore would be mid-Cretaceous in age. However, other Franciscan graywackes in the western part containing mid-Cretaceous fossils would, on the basis of the absence of K-feldspar, be assigned a Jurassic age. This contradiction indicates that the original assumption of a similar source for all the rocks was invalid and suggests that although the presence of more than a few percent of K-feldspar can be regarded as indicative of a Cretaceous age, the absence of K-feldspar is not necessarily diagnostic of age.

SPECIFIC GRAVITY OF GRAYWACKES OF THE FRANCISCAN AND GREAT VALLEY SEQUENCE

The specimens tested for K-feldspar content were also studied with regard to specific gravity, because specific gravity was thought likely to be another parameter in which the graywackes of the several upper Mesozoic units might differ. The results substantiate this belief, for as reported briefly by Irwin (1961), the median specific gravities of the graywackes of the three units of the Great Valley sequence are lower than that of the Franciscan graywacke, and their values decrease progressively with decreasing age.

The specific gravity was measured by means of a direct-reading balance with the hand specimen immersed in water. Most of the specimens are practically impermeable, and, for these, the measurements represent bulk specific gravity. However, some of the specimens, chiefly those from the Upper Cretaceous of the Great Valley sequence, are permeable, so the values obtained for these are a little higher than bulk specific gravity.

Cumulative frequency distribution curves based on the specific gravity measurements are shown on figure 27. The curves for the graywackes mapped as Franciscan are well separated from and on the high side of the curves for graywackes of the Great Valley sequence. The median specific gravity of specimens of

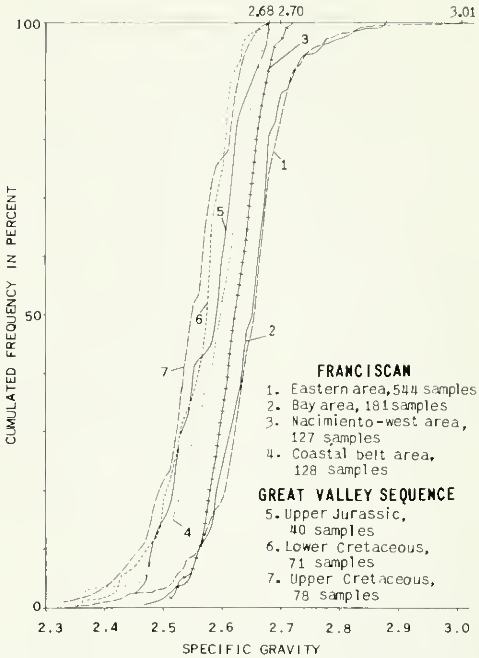


Figure 27. Cumulative frequency distribution curves for specific gravity of upper Mesozoic graywackes.

the eastern and Bay area of Franciscan is slightly greater than 2.65, whereas it is about 2.62 for the Nacimiento-west area and about 2.60 for the coastal belt. The marked decrease in slope of the upper tail of the Franciscan curves reflects metamorphism of the graywacke, as we have found most of the Franciscan graywackes with a specific gravity of 2.70, and all with a specific gravity of 2.71 or more, are metamorphosed. The metamorphism converts the plagioclase to the heavier jadeite and lawsonite. About 22 percent of the specimens of Franciscan graywackes have a specific gravity higher than 2.68, which is the highest specific gravity of any of the specimens of graywacke of the Great Valley sequence.

The curves representing the graywackes of the three units of the Great Valley sequence are progressively displaced toward the low specific gravity side of the graph with decreasing age of the units, although at some places the curves intermingle. Median values are 2.59 for the Upper Jurassic, 2.57 for the Lower Cretaceous, and 2.55 for the Upper Cretaceous rocks. As stated earlier, many of the values obtained for Upper Cretaceous graywackes do not truly represent bulk specific gravity, and thus the true curve for these rocks

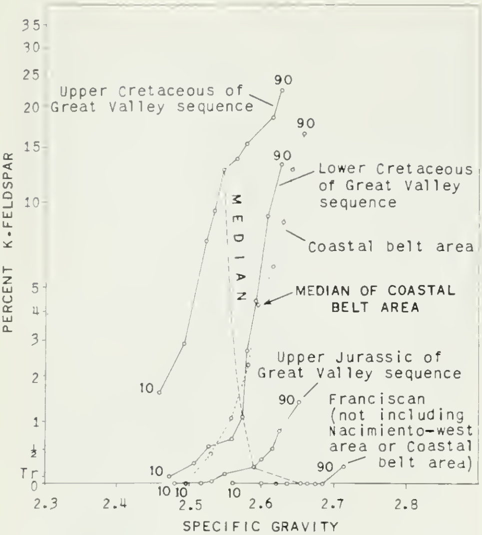


Figure 28. Percentile distribution of K-feldspar and specific gravity of upper Mesozoic graywackes.

should be even further to the left side of the graph than it is.

Reasons for the general differences in specific gravity of nonmetamorphosed graywackes (sp gr < 2.71) of the several units are not surely known, as data regarding the factors that might affect their density are not available. One might speculate, however, that the generally higher specific gravity of the Franciscan graywackes relative to the graywackes of the Great Valley sequence results from a greater abundance of mafic volcanic fragments (high specific gravity), a general lack of K-feldspar (low specific gravity), and a higher degree of compaction in the Franciscan graywackes. The progressive decrease in specific gravity with decrease in age of the Great Valley sequence probably is related to the marked increase in K-feldspar content with decreasing age, and to a progressively smaller amount of compaction resulting from shallower depth of burial.

The data regarding specific gravity and K-feldspar content of the graywackes of the various units are summarized in figure 28 by plotting 10-percentile points taken from curves shown on figures 26 and 27. The graph should not be interpreted as showing a relation between K-feldspar content and specific gravity of individual specimens. A nearly straightline relation exists between the three units of the Great Valley sequence along a line drawn through 50-percentile points. Along this line the Upper Jurassic, Lower Cretaceous, and Upper Cretaceous units occur in age sequence, the age increasing with increasing specific gravity, and decreasing with increasing K-feldspar content. The median line (fig. 28) was extended to the 50-percentile point for the Franciscan rocks in order to indicate the position of the point rather than to imply that the curve for the Franciscan is in age sequence relative to the curves for the three units of the Great Valley sequence. As stated earlier, however, this position relative to age may be valid for part of the Franciscan. The position of the curve for the "coastal belt" rocks approximates that of the Lower Cretaceous, but its 50-percentile point indicates both a higher specific gravity and higher K-feldspar content than does the 50-percentile point of the Lower Cretaceous of the Great Valley sequence.

Specific gravities of specimens of graywacke collected from the coastal belt are shown by a separate curve. A general lack of volcanic rocks, the sparse paleontologic data, and the results of the study of the K-feldspar content suggest an affinity with the Great Valley sequence. The cumulative frequency distribution curve for graywacke of the coastal belt also suggests this affinity, as this curve is close and generally parallel to the curves for the Great Valley sequence. Although generally somewhat to the right of the curves for those units, it is far to the left of the curve for the normal Franciscan graywacke. However, this cumulative frequency distribution curve for graywacke of the coastal belt includes some specimens with specific gravities above 2.68, higher than the highest specific gravity of any specimen collected from the Great Valley sequence.

AGE AND SOURCE OF THE FRANCISCAN

Although the fossiliferous part of the Franciscan ranges in age from at least Late Jurassic (Tithonian) to Late Cretaceous (Turonian), fossils are so sparse that the assemblage of Franciscan rocks might also contain extensive sequences of unfossiliferous rocks of older or younger age (see fig. 22). If older rocks are included, one might expect to find them in the eastern half of the outcrop area where most of the oldest fossils have been found. As shown in figure 25 and plate 2, in this area the Franciscan contains graywackes with no K-feldspar, thus suggesting that the graywacke may be pre-Knoxville, and in addition much of the Franciscan here is metamorphosed, in contrast to the adjacent Knoxville rocks which are unmetamorphosed. These features require a consideration of the maximum age that can reasonably be assigned to this eastern part of the Franciscan eugeosynclinal assemblage.

Additional data regarding the maximum age of the oldest Franciscan rocks might be obtained by: (1) considering the basement on which the Franciscan was deposited, (2) comparing the deformation and metamorphism of Franciscan rocks with nearby dated rocks of about the same age, (3) relating the miner-

alogy or lithology of Franciscan sedimentary rocks to possible source rocks of known age, (4) relating the Franciscan rocks to dated igneous intrusives, or (5) deducing the maximum age from what is known of the regional paleogeography or paleotectonics. We will consider in turn these various possibilities.

Basement

As no lower contact for the assemblage of Franciscan rocks has been recognized, the basement on which it was deposited is unknown. The only direct evidence regarding what is beneath the Franciscan is provided by the kinds of rocks brought up as inclusions in the igneous rocks that intrude the Franciscan. Inclusions have been found only in ultramafic intrusives, and although the relatively fresh plugs of dunite or peridotite seem to be devoid of inclusions, the serpentine masses not uncommonly contain inclusions ranging in size from less than a foot to tens of feet. Some of these inclusions are colored chert, graywacke, and greenstone, indistinguishable from normal Franciscan types. Most of the others that are metamorphosed are chemically closely similar to Franciscan rocks, although a positive correlation cannot generally be made because all primary textures are lost through recrystallization. The exceptions to this are the rodingites, which have radically different compositions owing to metasomatic reaction with the serpentine, but they show by relict textures that they might have been derived from Franciscan gabbros or greenstones (Schlocker, 1960). As the older crystalline rocks of the Coast Ranges, the Klamath Mountains, and the Sierra Nevada include quartzites, marbles, and some kinds of schists that are different from the rocks included in the Franciscan, the absence of these older rocks among the inclusions is real and not based on erroneous assignments.

Geophysical measurements have provided little useful data on the basement below the Franciscan. According to G. A. Thompson (oral communication, January 1961), gravity measurements indicate a lack of large density differences between crustal segments beneath Franciscan rocks and non-Franciscan rocks in western California. Magnetic data, according to G. D. Bath (oral communication, January 1961), have not been obtained over a large enough area in sufficient detail to suggest the character of the rocks below the Franciscan. Seismic measurements seem to offer considerable promise, but work to date has yielded chiefly data on the depth to the Mohorovicic discontinuity, which is generally agreed to be at about 30 km beneath the San Francisco Bay area, and discontinuities at higher levels are poorly known (Press, 1957). Cameron (1961) analyzed the records of several earthquakes in the area near Eureka and identified a P_F wave believed to travel chiefly in Franciscan rocks. This type of wave originates only from earthquakes with a focus of 10 km or less in depth, and along the Mendocino escarpment only earthquakes in the crustal segment east of the 1,000 fathom line yield this wave. Cameron's analysis of the December 21, 1954, Arcata earthquake indicated the coastal area was underlain by a 5.1 km/sec velocity layer to a depth of 3 km, a 5.95 km/sec velocity layer to a depth of 24 km, and a 6.93 km/sec velocity layer to 29 km where the "Moho" was reached. He assigned the upper 3 km layer to the Franciscan, the next 21 km to "granite," and the next 5 km to basalt. Perhaps the 3 km layer is better assigned to the Upper Cretaceous and Tertiary in the Eureka area, the underlying layer down to 24 km to Franciscan rocks, and the next layer below to basalt. Thus, the basement for the Franciscan might be older sedimentary rocks, granite, or basaltic crust. The inclusions in the serpentine suggest the Franciscan was deposited directly on basalt, peridotite, or serpentine, and the available seismic data when considered with the probable thickness of the assemblage also indicate that direct deposition of the Franciscan on a basalt substratum is a tenable hypothesis. However, as the type of basement is conjectural, this consideration does not aid in determining the age of the oldest Franciscan rocks.

Degree of Metamorphism Compared to That of Related Rocks

Some idea of the antiquity of the oldest part of the Franciscan might also be gained by comparing its metamorphism and deformation to similar features of nearby rocks of known age. We have mentioned that the Franciscan is generally more deformed than the Knoxville and that parts of the Franciscan are more metamorphosed. All contacts with rocks slightly older than the Knoxville are faults. In the northern Coast Ranges the Franciscan is for more than a hundred miles in fault contact with phyllite and greenschist of the South Fork Mountain and related ridges along the western boundary of the Klamath Mountains province, and these metamorphic rocks are at least in part of the Galice Formation (Irwin, 1960). The sharp contrast between these metamorphosed rocks and the unmetamorphosed Franciscan rocks in the northern half of the belt suggests the Galice, of middle Late Jurassic (late Oxfordian to middle Kimmeridgian) age, is older; however, farther south the contrast is not so great because the Franciscan rocks are also metamorphosed nearly to the same degree. Viewed broadly, however, the Galice Formation of the Klamath Mountains and the Mariposa Formation (Upper Jurassic) of the western Sierra Nevada, which are both widely intruded by granite and everywhere regionally metamorphosed, seem to be older than most of the Franciscan, which is only metamorphosed in some areas. Structurally, the Galice and Mariposa seem to be more tightly folded, but they do not exhibit the degree of

irregular superpositions of folding, flowage, and breakage which makes such a jumble out of many of the Franciscan exposures.

The Franciscan rocks also are in fault contact along the San Andreas and Nacimiento faults with a block of metamorphic and granitic rocks. The metamorphosed rocks, termed the Sur Series by Trask (1926), are generally considered to be Paleozoic in age and everywhere (Compton, 1960, p. 613) have a complicated history of repeated dynamo-thermal and high-temperature metamorphism. No traces of these periods of metamorphism are seen in the Franciscan rocks on the other sides of the boundary faults, even though all granitic intrusions into the Sur Series that have been dated are younger than the oldest known Franciscan rocks.

Heavy Minerals and Conglomerate Pebbles

The minerals in the Franciscan graywacke and the rocks occurring as pebbles in the conglomerate provide data regarding the age and source of the unit, though some of these data are contradictory. As the material that forms the graywacke is angular, and therefore presumably is first cycle detritus that has not traveled a great distance, it should be possible to relate it to a nearby source. By far the greatest amount of data available for the graywacke is the statistical information on its content of K-feldspar summarized previously in this report. We have indicated that for the bordering miogeosynclinal rocks of the Great Valley the amount of K-feldspar increases systematically with decreasing age. It seems safe to assume that the sources of K-feldspar are the granitic intrusives of the Klamath Mountains and Sierra Nevada, which have been shown to be of two ages by Curtis, Evernden, and Lipson (1958). One group, which is dominantly quartz diorite of Late Jurassic age, occurs in the Klamath Mountains and in the western foothills of the Sierra Nevada; the other, which is granodiorite-quartz monzonite of mid-Cretaceous age, forms the bulk of the plutonic rocks of the Sierra Nevada. So far as is known, K-feldspar is generally lacking in the pregranitic rocks of these areas, and thus the gradual increase in K-feldspar in the miogeosynclinal strata derived from the Klamath-Sierra terrane reflects the unroofing and erosion of the batholithic rocks. If the eastern Franciscan rocks lacking K-feldspar have a similar origin, as seems likely, they would by inference be older than the Knoxville part of the Great Valley sequence, which contains small amounts of K-feldspar. Similarly, the Franciscan graywacke of the western area that locally contains considerable K-feldspar must have been deposited after the batholithic rocks were partly unroofed. Studies of heavy minerals in the graywacke, summarized in figure 6, support this idea, as monazite is reported only from the western Franciscan rocks, and similarly zircon is much more abundant in the western rocks.

Curiously the data on the pebbles in the conglomerate (fig. 10) are contradictory. Geologists who have studied the conglomerates in the Diablo Range, in the eastern Franciscan area, report granite as one of the prominent rocks in the conglomerates from the Quien Sabe quadrangle northward to the Livermore quadrangle. This anomalous occurrence of granite-bearing conglomerate in a graywacke sequence containing no K-feldspar might be attributed to the use of "granite" as a field designation for all fairly light-colored, granular igneous rocks, but as several of the geologists also reported quartz diorite pebbles, this does not seem to be a valid explanation. The absence of K-feldspar in the accompanying graywacke suggests these well-rounded granite pebbles are reworked from some older conglomerates and do not represent erosion of granitic masses during this cycle of erosion. The other data on heavy minerals or conglomerate pebbles does not appear to be particularly diagnostic of age or source. Pyrite, rutile, and garnet, which may be derived from a metamorphic source, are practically absent in the eastern Franciscan rocks but common in the western ones. Other heavy minerals such as andalusite, kyanite, and piedmontite, which might indicate erosion of metamorphic rocks in the Sierra Nevada, or lawsonite and glaucophane, which would suggest cannibalistic erosion of older Franciscan rocks, do not seem to provide a pattern, either as to space or time, perhaps because the data are too scant or inaccurate.

Relation to Intrusive Rocks of Coast Ranges

The age of the Franciscan relative to either the Jurassic or Cretaceous granitic intrusives cannot be determined directly as no intrusive contacts have been found. Most of the granite in the Coast Ranges occurs in the giant sliver between the Nacimiento and San Andreas faults, and six granitic specimens from this block yielded mid-Cretaceous K-A dates ranging from 81.6 to 91.6 million years. (Curtis and others, 1958).* As fossils indicate that some Franciscan rocks are older than this, it is indeed curious that the Franciscan is nowhere known to be either intruded or metamorphosed by the granite. However, the recognition of the pregranite age of part of the Franciscan raises the

* New data obtained since this report was prepared suggest K-Ar dates obtained on the micas from the granitic intrusives of both the Coast Ranges and Sierra Nevada represent the latest time when the micas cooled to the fairly low temperature required for the retention of argon, rather than the time of the initial cooling of the magma following intrusion. Dates obtained from amphiboles are thought to more accurately date the intrusive period (Kistler and others, 1963). Hornblende from a "pluton" in the San Andreas fault zone in the Parkfield quadrangle gave a date of 143 million years (Hay, 1963, p. 113). Two-thirds of the intrusives of the Sierra Nevada that have been dated by K-Ar methods applied to their amphiboles, or by rubidium-strontium methods applied to whole rock samples, have yielded Jurassic ages (R. W. Kistler, oral communication, Dec. 1963). These Jurassic dates are more compatible than mid-Cretaceous dates with some of the concepts presented later in this report.

possibility that in the crystalline block west of the San Andreas fault some of the rocks now assigned to the Sur Series are really metamorphosed Franciscan rocks that have escaped detection during the limited study this area has received.

In the northern Coast Ranges there are two little-known occurrences of granitic rock that might be intrusive into the Franciscan. One of these, reported by Irwin (1960, p. 58), is in the Eureka quadrangle just north of the junction of U.S. Highways 101 and 299, a few miles north of Arcata. Here a coarsely crystalline syenite is poorly exposed on a brushy hillside and in a small quarry; limited field checking failed to find any contacts where its relation to the Franciscan could be seen. The other occurrence, reported to us by T. W. Dibblee (oral communication, 1959), is 1 mile west-northwest of the Barnwell Ranch in the Weott quadrangle. We have not seen this exposure, but, because it is close to a major fault separating Franciscan rocks from the Yager Formation of Ogle (1953), the granite may be an exotic tectonic sliver. Thus, although we can by inference relate the Franciscan to the granitic intrusives on the basis of the K-feldspar content of the graywacke, no direct evidence for the relative ages of the two rocks is available.

The ultramafic intrusives also are of little use in establishing the age or source of the Franciscan rocks, but for a different reason. Ultramafic rocks of presumed pre-Franciscan age occur in the Klamath Mountains and in the Sierra Nevada; these rocks also occur in both the older and younger parts of the Franciscan assemblage, and they locally intrude the older parts of the adjacent Great Valley sequence. Therefore, reported occurrences of serpentine, chromite, or picotite in the graywacke are not diagnostic either as to age or source.

Relation to Nevadan Orogeny

In considering the age of the oldest Franciscan rocks, an analysis of the mid-Mesozoic geologic history of the area is informative. Large quantities of rock were eroded from the Klamath–Sierra Nevada terrane after deformation of the strata of Kimmeridgian and older ages and after the intrusion of these strata by granitic rocks, but apparently before the deposition of the Knoxville Formation of Tithonian age. A part of the Great Valley sequence that is of Hauterivian age and that contains abundant coarse granitic debris is deposited on the eroded surface of the Shasta Bally batholith in the southern part of the Klamath Mountains, and farther south these rocks are a part of an apparently conformable sequence extending downward through the Knoxville. However, so far as is known, the Knoxville nowhere laps onto the deformed, metamorphosed, and intruded rocks of the Klamath Mountains. Thus, while it can only be inferred that the Nevadan orogeny in the Klamath Mountains antedated the Knoxville, the map pattern showing the overlap of the Klamath Mountains by the little disturbed Great Valley sequence is most suggestive of this relation. A contrary interpretation based on a K-A date of 134 m.y. for the Shasta Bally intrusive requires nearly contemporaneous intrusion of this rock and deposition of the fine-grained Knoxville Formation within 25 miles (Curtis and others, 1958). However, it scarcely seems possible that the batholith was intruded, uplifted, stripped of a thick cover, and yet retained considerable relief while the conformable miogeosynclinal sequence was encroaching on it; thus, the correlation of the paleontologic and K-A date seems suspect. If we assume that the Knoxville is younger than the earliest phases of the Nevadan orogeny, during which the Galice Formation and older rocks of the Klamath–Sierra Nevada were folded, faulted, intruded, and eroded, the oldest part of the Franciscan probably was formed of debris eroded during this period. Thus, the oldest part of the Franciscan probably is younger than the Galice Formation (late Oxfordian to middle Kimmeridgian) and older than the Knoxville Formation (Tithonian). The geographic extent of these Franciscan rocks west of and parallel to the Klamath Mountains and Sierra Nevada for hundreds of miles, is a suitable position for collection of the erosion products; and the composition of the older Franciscan graywacke, with its general lack of K-feldspar, is compatible with derivation from a nearby rising metamorphic terrane.

Relation to Rocks of the Knoxville Formation

If some of the Franciscan in the eastern area close to the miogeosynclinal strata of the Great Valley is pre-Knoxville in age, as has been suggested, it is reasonable to wonder if Franciscan rocks grade upward into the Knoxville, as suggested by Taliaferro (1943a, p. 194, 208-212), or if in some places they are unconformably overlain by the Knoxville. These seemingly simple queries prove to be surprisingly difficult to answer. That Franciscan rocks lie below Knoxville rocks is most clearly established in the Diablo Range, especially at Mount Diablo, where a piercement of the Franciscan has been pushed upward through an arch of fossiliferous Knoxville and younger strata (fig. 30). Here, as elsewhere, the Franciscan rocks are highly deformed in contrast with the structurally simple, broad flexure of Great Valley strata which they intrude. This difference in degree of deformation suggests that the Franciscan has been subject to deformation prior to deposition of the Knoxville. However, this difference should be interpreted with caution as elsewhere Franciscan rocks of Cretaceous age are more deformed than are adjacent older or coeval rocks of the Great Valley sequence, therefore indicating that the structural history was very complex and that intense deformation is not indicative of age.

One problem in determining the relation of the Franciscan to the Knoxville, however, arises from the lack of agreement about what features are diagnostic

of rocks of the two facies. We have indicated that in some places greenstone and chert are interlayered with thick sections of clay shales containing Upper Jurassic fossils; the clastic rocks are like those of the miogeosynclinal facies, but the greenstone and chert are typical of the eugeosynclinal facies. Such sequences are generally assigned to the Knoxville Formation because of the abundance of fossils. The occurrence of these hybrid rocks in the lower part of the Knoxville led Taliaferro to treat the Franciscan and Knoxville together as the Franciscan-Knoxville Group (Taliaferro, 1943a, p. 214), and he believed that these occurrences indicated gradational relations, with the Knoxville lying above older parts of the Franciscan. In the Nipomo, Wilbur Springs, and Morgan Valley quadrangles, cited by Taliaferro as places where the Knoxville grades downward to the Franciscan, we believe the gradational relation is far from clear. In these areas the fossiliferous Knoxville, containing greenstone and chert, is the lower part of a virtually conformable miogeosynclinal sequence, but the Knoxville does not grade downward into a typical assemblage of Franciscan graywacke. Typical Franciscan rocks are either separated from the Knoxville rocks by a fault or by a serpentine mass, and these Franciscan rocks are considerably more deformed. Because of the prevalence of faults or serpentine between rocks of the two facies, we know of no place where one can see a gradation from typical Franciscan rocks into the Knoxville, if the latter is defined on the basis of the character of its sedimentary rocks or its relation to younger miogeosynclinal rocks, rather than on the basis of the occurrence of greenstone or chert.

Unconformable relations, with Knoxville deposited on deformed Franciscan, have also been described. In the Hayward quadrangle (Robinson, 1956) and the Panoche Valley quadrangle (Enos, 1963) supposed Franciscan rocks, consisting of tuff, tuff-breccia, and pillow accumulations of keratophyre and other volcanic rocks, are overlain by fossiliferous Upper Jurassic conglomerate, sandstone, and shale of the Great Valley sequence. The relation of these volcanic rocks to nearby Franciscan sedimentary rocks, some of which are metamorphosed, is either one of juxtaposition by faulting or else is indeterminable. Thus, while structural evidence seems to indicate that some Franciscan rocks are pre-Knoxville in age, we feel that nowhere has a depositional contact, either conformable or unconformable, of Knoxville rocks on typical Franciscan sedimentary rocks, been demonstrated.

Upper Age Limit

The upper age limit of the Franciscan also cannot be determined precisely. Fossils of Late Cretaceous (Turonian) age, found in a typical eugeosynclinal assemblage in the Skaggs quadrangle, indicate the eugeosynclinal environment persisted at least until Turonian time. Somewhat younger fossils of Campanian age have been found in argillite associated with graywacke in rocks mapped as Franciscan on the Marin peninsula. These rocks, however, are not typical Franciscan sedimentary rocks as they are in thin, well-defined beds, are cleaner, and are not known to be directly associated with mafic volcanic rocks or chert, so their assignment to the Franciscan eugeosynclinal rocks is open to question.

As was the case with the older Franciscan rocks, difficulties are encountered when one looks for places where the younger Franciscan rocks grade to the Great Valley sequence. Franciscan rocks of mid-Cretaceous age occur principally along the western part of the outcrop belt from the San Juan Bautista quadrangle northward to Trinidad Head. A large part of this area is occupied by the "coastal belt" rocks, which are intermediate in character between the typical Franciscan rocks and the Great Valley sequence, but south of Healdsburg much of the Franciscan is a typical eugeosynclinal assemblage. Miogeosynclinal strata of post-Franciscan (late Late Cretaceous) age occur in this area in several places, for example, on the divide west of New Almaden (Los Gatos quadrangle), on the Stanford University campus (Palo Alto quadrangle), probably at San Bruno Mountain (San Mateo quadrangle), and in the Mount Tamalpais and Petaluma quadrangles; but no gradational relations between these rocks and the Franciscan rocks have been recognized. The eugeosynclinal Franciscan rocks of the San Francisco Bay area are, at least in part, time equivalents of the "coastal belt" rocks farther north, but mapping is too incomplete to permit an understanding of the exact facies relations. Similarly, the "coastal belt" rocks may be conformably overlain by the Late Cretaceous Yager Formation of Ogle (1953), though here also mapping is too sketchy to confirm this.

It is curious that nowhere does the Franciscan clearly grade either laterally or vertically into the Great Valley sequence, despite the fact that the two facies were being deposited contemporaneously through an appreciable segment of geologic time. Equally curious is the fact that nowhere has the Franciscan been found to lie depositionally on the Great Valley sequence, even though the youngest Franciscan rocks are clearly younger than some parts of the Great Valley sequence.

Source of the Franciscan Sediments

The source of the older, pre-Knoxville, Franciscan rocks seems most likely to be the ancestral Klamath Mountains and Sierra Nevada lying east of the depositional area. The source of some of the debris forming the younger Franciscan rocks probably also lay in the same area, but it seems unlikely that this could have been the source of all the younger Franciscan rocks. Specifically, in the San Francisco area, west of the Hayward fault, Franciscan rocks of mid-Cretaceous age commonly contain little or no K-feldspar, in contrast to the several percent generally found in strata of similar age in the Great Valley sequence in the East

Bay area and elsewhere. As the Great Valley sequence undoubtedly was derived from erosion of the Klamath-Sierra Nevada terrane, it seems improbable that the dissimilar Franciscan rocks of the Bay area had the same source. Thus, for these rocks, we must look for a different source area to the east or for a western source. Either of these seems to be a possibility. During mid-Cretaceous time the block west of the San Andreas fault probably was subjected to erosion and may have shed sediment to the east, or the source may have been the uplifted central part of the Diablo Range, since a stratigraphic hiatus in the Great Valley sequence on its east flank indicates that this area may have been subject to erosion at some time during the interval from Hauterivian to Cenomanian. The average K-feldspar content of the "coastal belt" rocks farther north is compatible with their having the same source as the miogeosynclinal rocks of similar age, but this belt contains a larger proportion of graywackes with no K-feldspar, which may indicate some derivation from a western source or cannibalism of local exposures of older Franciscan rocks. The uncertainties regarding source area can perhaps be removed by careful heavy mineral studies, but the data now available are inadequate.

In summary, the oldest Franciscan rocks seem likely to be older than latest Jurassic (Tithonian) on the basis of their occurrence beneath the Knoxville, their greater degree of deformation and metamorphism, their lack of K-feldspar, and their appearing to have been formed of the debris eroded from the deformed Klamath Mountains and Sierra Nevada during and immediately after the earliest phase of the Nevadan revolution. None of these criteria alone is conclusive, but considered together they make a pre-Knoxville age for the eastern Franciscan rocks a strong probability. The present distribution of the pre-Knoxville Franciscan is shown on figure 24, 1. The youngest Franciscan rocks are at least Turonian in age as indicated by fossils, and these rocks occur in the western part of the outcrop belt. Scattered occurrences of fossils of Late Jurassic, Early Cretaceous, and Late Cretaceous ages in the

Photo 77. Shear zone showing scattered tectonic blocks of schist and other hard rocks engulfed in a matrix of sheared, soft rocks, which give rise to landslides.

Franciscan suggest that eugeosynclinal rocks were being deposited somewhere in the Coast Ranges at all times from pre-Tithonian through Turonian time (see fig. 24, 2, 3, 4, 5). Although we believe it is possible to identify areas of deposition of "older" and "younger" Franciscan rocks, we are unable to place rigid temporal or spatial boundaries on these two units at this time. Gradational relations between the eugeosynclinal Franciscan rocks and the coeval Great Valley miogeosynclinal rocks have not yet been found. The older Franciscan rocks probably were derived from a landmass to the east, and although an eastern source for some of the younger Franciscan rocks is indicated, for others either a western source or cannibalism of uplifted older Franciscan rocks is required.

STRUCTURES

On previous pages we have suggested the most likely ages for Franciscan rocks found in various areas and have mentioned the relation of older and younger parts of the Franciscan to the partly contemporaneous Great Valley sequence. To readers who are not familiar with the structural complexities involved, it may seem strange that, in spite of the scarcity of fossils, these different ages had not become apparent earlier through the application of normal stratigraphic and structural methods. For these readers additional background regarding the structural complexities must be provided before we discuss the late Mesozoic history of the Coast Ranges. The following paragraphs first briefly describe some of the more unusual internal structural features of the Franciscan rocks and explain why normal stratigraphic methods are almost useless in determining the broader structures within the assemblage of Franciscan rocks. Then, the major structural units in the Coast Ranges are outlined to show their relation to the Franciscan rocks and to the problems posed by the present distribution of the Franciscan.

Structures in Franciscan Rocks

Both major and minor structures in nearly all areas of Franciscan rocks are inadequately understood, in spite of the mapping that has been done by many competent geologists over a period of more than half a century. This is not a result of poor exposures or lack of effort but is the result of inherent features of the rocks. In less well exposed areas in many other regions the major structures have been ascertained, and regions that probably have more complicated geology have yielded their structural story upon careful study. The chief reason for our lack of knowledge of the structure of the Franciscan results from the persistence of its heterogeneity. Although different kinds of rocks are present, none, except perhaps the rare discontinuous lenses of limestone, are sufficiently distinctive to be used as a key bed or horizon marker, nor have unique sequences that might be given formational status been recognized. Thus, in mapping one must resort to the delineation of whatever kinds of rocks can be differentiated in each local area, and because of the general primary irregularity and discontinuity of these units even this generally fails to yield satisfactory results. Partly as a result of these inherent difficulties and partly because so much of the Franciscan terrane is yet unmapped in detail, many major structures doubtless remain virtually unknown. However, enough is known to warrant a few statements regarding the general pattern of deformation and kinds of structures recognized in the Franciscan.

Small structures that can be seen in a single outcrop, or a group of closely spaced outcrops, are better known than structures extending over larger areas, simply because they can be readily observed rather than worked out by mapping. Among the small structures, shears or minor faults predominate, and they are so common that they can be seen in nearly every exposure that is more than a few feet in size. Many of the shears are nearly parallel to the bedding, and thus form an irregular boudinage or disrupt the continuity of the beds. The majority of these shears probably result simply from the folding of the strata, but some have relations to drag folds that indicate they have a different origin. Less common, but nevertheless abundant, are other fractures or faults cutting the beds at steep angles. Irregular cracks that shatter the more competent rocks are also a common feature in parts of the Coast Range. Many outcrops also exhibit irregularities in bedding, either due to folding or flowage, to such an extent that it is difficult to obtain any meaningful strike and dip. However, slaty cleavage is generally not developed, and the plunges of axes of minor folds do not seem to define any pattern even locally, although this has not been tested by systematic mapping.

Larger structures that must be deciphered by mapping are less well known. Measurements of bedding or delineation of lithologies indicate the structural grain trends northwesterly, with what appear to be the oldest structures trending west-northwest and younger structures trending more nearly northwest. Clearly a preponderance of the rocks dip eastward, but locally west dips suggest open folds. Mapping of distinctive rock units, such as masses of greenstone, reveals that some major units have a continuity that is surprising in light of the prevalence of faults seen in outcrops or roadcuts, and thicker greenstone masses can be traced for many miles. The margins of such mappable units, however, are generally so irregular that it is difficult to interpret their dip from the relation of the trace of the contact to the topography. Rarely do lithic units map out in arcuate shapes indicative of axial portions of plunging folds, which suggests that dislocation by faulting in these parts of the folds is common. The beds may be isoclinally folded, but dips are generally not near vertical, slaty cleavage is rarely developed, and places where beds have been found to be over-

Photo 78. Area of slides and scattered resistant blocks characteristic of shear zones in the Franciscan terrane. Looking north to Blue Rock on the Bell Springs road in the Leggett quadrangle. Red Mountain ultramafic plug underlies the dark area beneath skyline on left edge of photograph.

turned are uncommon. Although some thrust faults have been mapped where the Franciscan overrides younger rocks, the mapping of various lithologies within the Franciscan has in only a few places revealed internal thrust faults.

Steep northwesterly trending faults are a major, and doubtless the dominating, structure in the Coast Ranges. Some of these faults with large components of strike-slip movement, such as the San Andreas, Hayward, and perhaps also the Nacimiento fault, are well known; but within the Franciscan terrane, especially in the northern Coast Ranges, others with probably large offset have been identified though they remain inadequately mapped. Other major faults with similar northwestern strike but a large vertical component of displacement are believed to be chiefly responsible for the more recent uplift of different blocks in the Coast Ranges, but where these faults cut through the Franciscan it is difficult to identify them unless younger rocks are also present, or unless they have recent movement and topographic expression.

Faults within the Franciscan terrane are not easily detected because the trend of most of them nearly coincides with the prevalent structural grain that is due to folding. Furthermore, the ones we suppose have the greatest movement formed broad shear zones that are not nearly as obvious as the relatively inconsequential faults seen in so many roadcuts or natural exposures. Typical shear zones are up to a mile in width with outward gradational relations with the less sheared, normal Franciscan rocks. Such zones consist of blocks of the different harder varieties of Franciscan rocks embedded in a more sheared "matrix." As shear zones do not seem to be appreciably more easily eroded than the surrounding rocks, the zones are as likely to trend along slopes or ridges as along canyon floors. Their presence is often suggested by the blocky character of the terrane, by the prevalence of landslides, or by the fact that they generally are covered with grassland which contrasts with the surrounding forest or brush. The blocks within the zones range in size up to hundreds of feet, so that the largest are

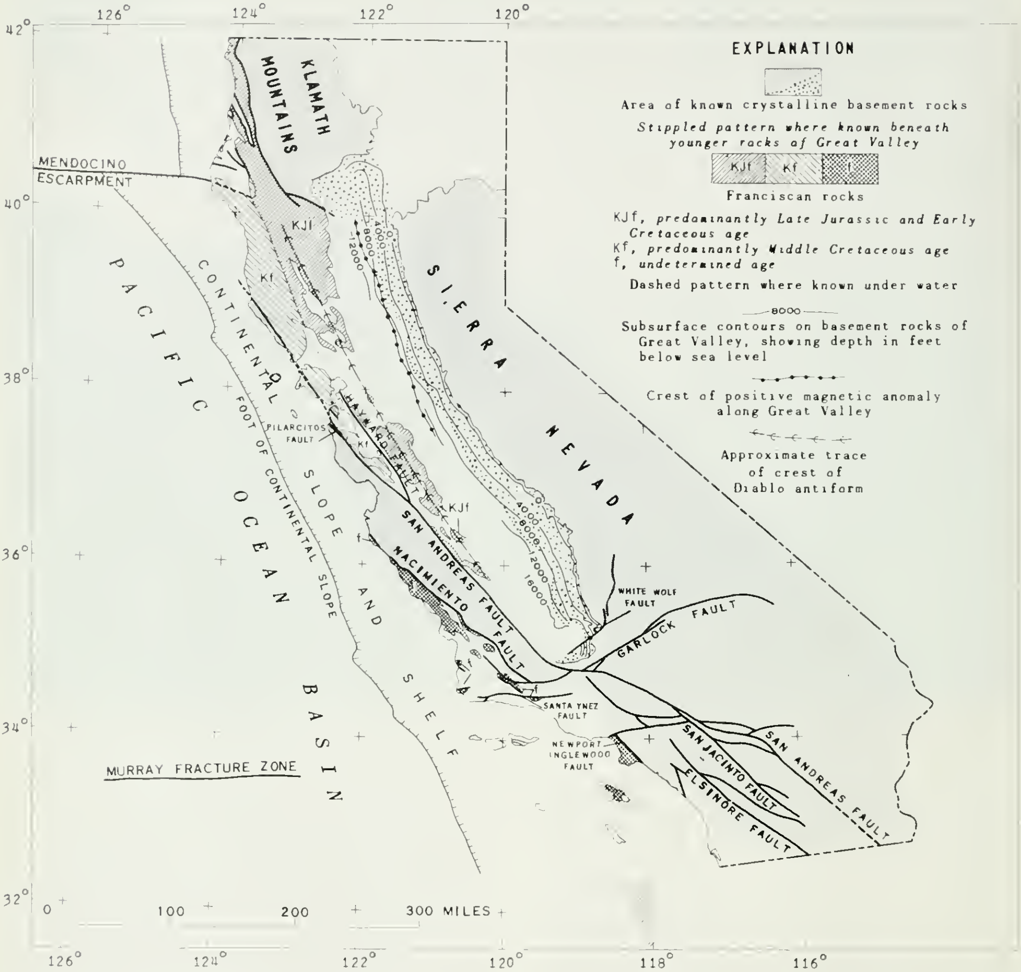


Figure 29. Map showing principal structural features of western California and offshore area. Subsurface contours on basement rocks of Great Valley from Merrit Smith (unpublished). The Mendocino escarpment is from Menard (1955b), the Pioneer Ridge fault from Menard (1960), and the Murray fracture zone from Menard (1955a). Faults shown in southern California are from Cohee (1961). Areas of underwater bedrock off the coast of southern California are after Emery (1960). Areas of crystalline bedrock off the coast of northern California are after Hanna (1952) and Chesterman (1952). Trend of crest of magnetic high of the Great Valley after Irwin and Bath (1962). Foot of continental slope after U.S. Geological Survey map of State of California, scale 1:1,000,000, edition of 1953.

mappable without exaggeration on a 15-minute quadrangle scale. Where such zones are carefully mapped, the diverse lithologies of adjacent blocks provide good evidence for the existence of the shear zone. Serpentine commonly occurs in these zones, as also do the large rounded tectonic inclusions of glaucophane schist or eclogite. Because of the presence of serpentine and the sheared nature of much of the rock, landslides are another characteristic feature of the shear zones, although not all slides originate in them. The recognition of these shear zones, which are as yet largely unmapped, is of great importance in determining the geologic structure, and because of the unique physical properties of the shear zones their recognition is also of utmost importance in the planning of highways, dams, and larger buildings (Bonilla, 1961).

Larger Structures of Coast Ranges

The preceding statements regarding the internal structures of the Franciscan indicate the difficulty of obtaining meaningful structural data even through detailed mapping of the Franciscan rocks. Such normally simple things as determining the positions of anticlines and synclines are made difficult, if not impossible, by the local crumpling that leads to erratic strikes and dips, by the lack of continuity in distinguishable units from one limb to another, and by the prevalence of faults in the axial areas. Even more difficult are the problems presented by the major shear zones, as the lack of recognizable units generally precludes correlation across such zones. The net result of these complexities is that the study of structures within the Franciscan, so far, permits only the conclusion that it is complexly deformed, both by folding and faulting, with the development of a northwesterly trending grain. Fortunately the larger structures of the Coast Range, which are those of greatest concern in working out the major events in the geologic history, also involve the Great Valley sequence and other rocks that do not present this internal complexity. In the following paragraphs we will discuss the larger structures and the structural units that they define.

Terranes with and without crystalline basement. The major structural features of western California and the related offshore area are shown on figure 29. Within this area there are two types of structural terranes: those known from surface geology and by drill holes to have a basement of crystalline (metamorphic or plutonic) rock, and those that are not known to be underlain by crystalline rock and which may have a basaltic or peridotitic basement. Terranes with a crystalline basement locally have a cover of Cretaceous strata of the Great Valley sequence and younger rock. The cover is generally less than 15,000 feet thick and, in most places, is only broadly folded and cut by few major faults. In contrast, terranes not known to be underlain by crystalline rock may contain sedimentary accumulations which are many tens of thousands of feet thick, and they are generally more tightly folded and cut by more and larger faults. The Franciscan rocks are confined to terranes without known crystalline basement.

The crystalline basement of western California consists of sedimentary and volcanic rocks ranging in age from Precambrian or early Paleozoic to middle Mesozoic (middle Kimmeridgian) and intruded by granitic rocks of late Mesozoic age. These rocks are exposed in the Klamath Mountains, in the Sierra Nevada, and in a block lying between the San Andreas and Nacimiento faults. The terranes without known crystalline basement are those containing Franciscan rocks, but in many places these rocks are extensively covered by other sedimentary strata. As we have indicated, it seems likely these areas of Franciscan rocks are underlain only by basaltic substratum or ultramafic rock, and not by "crystalline rocks," if this term is used to apply to metamorphic or plutonic igneous rocks. The contacts between the structural units with these two basements are, so far as is known, all faults.

Western boundary of Klamath–Sierra Nevada basement. In the northern Coast Ranges the crystalline rocks of the Klamath Mountains are in fault contact with Franciscan rocks from the Oregon border southward for 150 miles to a point in the southwestern part of the Colyear Springs quadrangle (Irwin, 1960, p. 60). South of this point the boundary fault apparently divides into several branches, the relative importance of which is not yet clearly understood. Two branches extend into the miogeosynclinal strata of the northern Great Valley where they produce an offset of a few miles that may be interpreted either as left-lateral strike slip or down on the northeastern side. Although the Knoxville strata that are prominent on the west side of the northern Great Valley have been reported to extend across these faults, no Upper Jurassic fossils have been found north of them. The amount of offset along these branches, indicated in the Great Valley sequence, seems inadequate to explain the major separation of the Klamath Mountains and Coast Range rocks and suggests either a major movement in pre-Knoxville time, or a later movement that has been taken up by another branch fault. A third branch of the major fault probably does diverge at about the same point and follows the great serpentine mass that extends southward marking the general boundary between the Franciscan and the Great Valley sequence. Unfortunately, the movement along this branch has not been determined. This boundary, however, should not be interpreted as the western extent of the crystalline basement, for geophysical data suggest this basement terminates beneath miogeosynclinal rocks farther east in the central part of the Great Valley. From the Colyear Springs quadrangle southward, all the way to the mountains south of Bakersfield, the position of the western edge of the crystalline basement is not known. Wells drilled along the east side of the Great Valley

Photo 79. Aerial view north along coast from a point just south of Ocean Cove, Plantation quadrangle, about 35 miles south of Pt. Arena. Prominent valley follows path of the San Andreas fault. Rock to the left of fault are Gualala Formation of Weaver (1943); rocks to the right of the fault are Franciscan.

have reached crystalline basement at depths of 12,000 feet and less, but on the western side the sedimentary strata are so thick that the rocks underlying them have not been reached.

San Andreas fault, western boundary of some rocks without crystalline basement. The San Andreas fault is the western limit of the thick sedimentary prism with unknown basement. This prism includes the Franciscan of the northern Coast Ranges and Diablo Range and the overlying portions of the Great Valley sequence. The San Andreas fault cuts gradually from the eastern to the western side of the Coast Ranges as it trends northward from the south end of the Great Valley to Point Arena. Where or how far it goes beneath the Pacific Ocean is controversial. Some geologists, for example Tocher (1956), point to the occurrence of earthquake epicenters along its projection north of the Mendocino escarpment as indicating that the fault goes past this great crustal feature, while Shepard (1957), notes the occurrence of epicenters to the west along the escarpment, and the lack of disruption of submarine topography or geomagnetic anomalies north of the escarpment, as indicating that the fault turns westward into the Mendocino escarpment. In either case, throughout its Coast Range extent, and by inference in its offshore extent, the San Andreas fault separates two distinctly different structural units. On the west side is a crystalline block with granitic plutons and no known sedimentary rocks of Late Jurassic to Late Cretaceous (pre-Campanian) age; on the east is a vast thickness of Late Jurassic to Late Cretaceous eugeosynclinal and miogeosynclinal strata. Obviously the San Andreas fault is a major crustal structure that plays an important part in the late Mesozoic history of the Coast Ranges, and in a later part of this report we will discuss various ideas regarding its origin and the supposed large lateral displacement along it.

Photo 80. Aerial view southeast along the path of the San Andreas fault. Bodega Bay in central part of picture, with adjoining Tomales Bay extending southward along the fault. Rocks to the left of the fault are Franciscan overlain by Merced Formation; rocks to the right are chiefly quartz diorite overlain by Monterey Shale.

Nacimiento fault, western boundary of a sliver with crystalline basement. The crystalline block lying west of the San Andreas fault is a sliver only about 40 miles wide but at least 300 miles long. It is bounded on its western side by the Nacimiento fault, which extends on land from near the northeastern corner of Santa Barbara County northward to Point Sur, and probably continues northward beneath the ocean a similar distance. The Nacimiento fault is not so well defined as the San Andreas fault, for in some places the Nacimiento is overlapped by Late Cretaceous or younger strata through which no continuous break has been found. Its continuity as a single fault has not been verified by mapping either along its central part, southwest of Paso Robles, or at its southern end where it probably joins the Big Pine fault. Unlike the San Andreas fault, it has no record of recent movement, nor has it been the locus for earthquakes. The crystalline block extends north at least as far as the granitic Farallon Islands, and granitic rocks have been recovered by dredging northwest of Point Reyes (Hanna, 1951). An extension still farther northward is suggested by the occurrence of 8-foot granite boulders in the Gualala Series of Weaver (1943) near Black Point (Plantation quadrangle). The projection of the Nacimiento fault reaches the continental margin near the latitude of the mouth of the Russian River, and, as the continental margin extends north from this point nearly in line with the fault, the Nacimiento fault may form the continental margin northward to the Mendocino escarpment. Great lateral movement on the Nacimiento fault has not been seriously proposed, but the occurrence of metamorphic rocks of the granulite and amphibolite facies on Cone Peak in the Santa Lucia Range (Compton, 1960, p. 634) indicates the crystalline block must have been uplifted many miles relative to the unmetamorphosed rocks lying on either side of it.

Area west of Nacimiento fault, without crystalline basement. West of the Nacimiento fault is another area of thick sedimentary rock resting on unknown basement. There Franciscan rocks are prominently exposed in a narrow sliver extending northward from San Luis Obispo to Point Sur, and they also crop out to the south in a few places in the Transverse Ranges as far east as Santa Barbara. South of this point, the Franciscan eugeosynclinal assemblage is represented only by metamorphic rocks exposed in the Palos Verdes Hills and on Santa Catalina Island. Thus, the area of exposure of Franciscan rocks west of the Nacimiento fault is small as compared to the area east of the San Andreas fault, but, if the Franciscan extends to the edge of the wide submerged continental platform off the southern coast (fig. 29), the two areas with unknown basement are comparable in size.

In addition to these great faults which separate the main structural blocks of the Coast Ranges there are a few other major features that either are responsible for the gross distribution of the rocks or at least pertain to their gross distribution.

Mendocino escarpment. Studies of the Pacific Ocean basin made in recent years have indicated the presence of major crustal breaks lying offshore from the Coast Ranges and trending nearly east, in contrast to the northwesterly grain of the Coast Ranges. At least one of these, the Mendocino escarpment that has been previously mentioned, offsets the continental margin and seems surely to have some bearing on the distribution of the structural units of the Coast Range. Other crustal breaks such as the Murray and Pioneer Ridge fracture zones (fig. 29), have not been shown to reach the continental margin and thus are neglected in this report.

The Mendocino escarpment, which extends westward from the California coast for at least 1,400 miles, is interpreted as a fault along which the north block is upthrown so that the ocean floor on the north side is about half a mile higher than the floor to the south (Menard, 1955b). According to Vacquier, Raff, and Warren (1961), a match of the geomagnetic anomalies on the two sides of the escarpment indicates a *left-lateral* slip of 735 miles along the escarpment. The continental margin, however, shows offset of about 75 miles in a *right-lateral* sense (fig. 29), and a swing in trend of the geomagnetic anomaly pattern over the continental shelf from south to southwest as the escarpment is approached from the north (Mason and Raff, 1961, p. 1260) also suggests drag due to right-lateral movement. An onshore continuation of this fault zone is indicated by an east-trending fault extending inland from Petrolia (Cape Mendocino quadrangle), along which there appears to be a post-Late Cretaceous right-lateral offset of 12 miles. Farther inland the fault separating the crystalline rocks of the Klamath Mountains from the Franciscan rocks to the west turns abruptly from the south-southeastern trend, along which the fault extended south from the Oregon boundary, to an east-southeasterly trend at the point where the fault would intersect an eastward prolongation of the Mendocino escarpment fault zone. West of this turn, however, no evidence of an easterly trending fault has been found in the Franciscan.

Hayward fault. The terrane east of the San Andreas fault is divided into two somewhat different structural units by the Hayward fault, which branches eastward from the San Andreas fault about 35 miles southeast of Hollister (fig. 29). This fault is similar to the San Andreas in having recent right-lateral movement and being currently active. From its point of divergence from the San Andreas, the Hayward fault extends northward through Hollister, along the west side of part of the Diablo Range, and through the campus of the University of California at Berkeley. Its path north of Berkeley is not well-known, but it may continue as either a single fault or a series of *en echelon* faults along the eastern limits of the "coastal belt" rocks. Along its known path the Hayward fault separates a much faulted western area of dominantly mid-Cretaceous Franciscan rocks from a less faulted area in which older Franciscan rocks are partly overlain by Upper Jurassic through Cretaceous strata of the Great Valley sequence.

Diablo antiform. The rocks extending from near Parkfield to Mount Diablo, east of the known path of the Hayward fault, are broadly folded into an arch which in this report we designate the Diablo antiform (fig. 29). The axis of the Diablo antiform trends northwest, along the middle of the area containing rocks we have referred to as older Franciscan. As the crest of the antiform has been breached along much of the Diablo Range by erosion of either broad folds or piercements, the Franciscan that normally lies below the mantle of the Great Valley sequence is widely exposed along the axial part. North of Mount Diablo the antiform is not so well defined, but as far north as Clear Lake the gross form of the arch can be deduced from the fragmentary remnants of the mantle of miogeosynclinal rocks. Although the antiform very likely extends north of Clear Lake, insufficient structural information is available to accurately plot the position of its axis through the northern Coast Ranges.

Broad *en echelon* cross folds and piercements are prominent structures along the Diablo antiform. The folds are clearly developed in the Great Valley sequence and in the Tertiary, but they are less readily apparent in the Franciscan. They trend southeast, diverging at low angles from the trend of the Diablo antiform and San Andreas fault, and plunge gently toward the Great Valley. In the northern Coast Ranges the best documented fold of this system is in the Wilbur Springs quadrangle. There the Upper Jurassic and Lower Cretaceous units of the Great Valley sequence are folded into an antiform and complimentary synform that plunge southeast, with serpentine and Fran-

Photo 81. Aerial view of Mt. Konocti, a Recent dacitic volcano on the southern shore of Clear Lake in the Kelseyville quadrangle. Both the Clear Lake volcanic field and another field of similar size lying largely in the Quien Sabe quadrangle are along the axial part of the Diablo antiform.

ciscan rocks underlying the Knoxville and forming the core of the antiform; but the folds are barely evident in the overlying Upper Cretaceous unit of the Great Valley sequence. In the southern Coast Ranges the major folds of this system are evident chiefly along the southern part of the Diablo Range where they are shown mainly by the Upper Cretaceous of the Great Valley sequence and by the Tertiary strata.

Piercement structures. Piercement structures have been described chiefly in connection with the study of quicksilver deposits of the southern Coast Ranges. Most of these are internally complex structures in the core of the Diablo antiform, and they consist of serpentine and other Franciscan rocks that have punched upward through the overlying rocks of the Great Valley sequence. Mount Diablo is a piercement that consists essentially of an oval area of Franciscan rocks and diabase separated by a band of serpentine. These rocks are bounded around the base of the mountain by steep faults and are surrounded by strata of the Great Valley sequence that generally dip steeply away from the boundary faults (fig. 30). The New Idria piercement in the southern part of the Diablo Range consists of an ovate mass of serpentine, with a thin cover of Franciscan rocks in its southern part, that has pushed up through and locally overturned Cretaceous strata of the Great Valley sequence (fig. 31). The piercement is nearly 15 miles long, over 4 miles wide, and elongate in a west-northwesterly direction. It is believed to have pushed upward to the surface in several different periods, as abundant serpentine debris occurs in nearby rocks of Late Cretaceous, late middle Miocene, and Pliocene age (Eckel and Meyers, 1946, p. 94-95). Another piercement of smaller size that occurs northeast of Parkfield consists entirely of serpentine; it intrudes rocks as young as Miocene (Bailey, 1942). Page and others (1951) describe a piercement in the area north of Santa Barbara that differs in that it consists entirely of Franciscan rocks with the harder varieties forming cohesive masses in a matrix of sheared

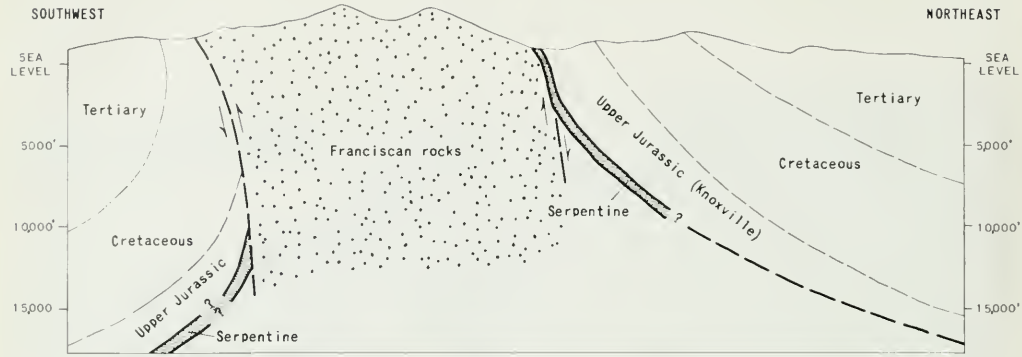


Figure 30. Idealized cross section of Mount Diablo, in part after Pampeyan (1963) and Taliaferro (1943b).

Photo 82 (below). Aerial view east toward Mt. Diablo from a point 5 miles northwest of Walnut Creek. Mt. Diablo is a diapiric intrusion of Franciscan rocks into arched rocks of the Great Valley sequence. The oldest rocks of the sequence intruded here are black shales containing *Buchia piochii* and have been assigned to the Knoxville.

shale. Such piercements may be more common within Franciscan terranes than has been supposed since these piercements would be difficult to recognize unless they intruded some other kind of rock. Also not generally recognized as a piercement, perhaps because of its large size, is the entire Franciscan core of the Diablo Range. This core is in most places separated from strata of the Great Valley sequence by steep faults, some of which dip inward and have reverse movement (Leith, 1949; Briggs, 1953a; Maddock, 1955; Schilling, 1962).

Reverse faults. Within the structural units with unknown basement, particularly close to the San Andreas and Nacimiento faults, there are many other steep, nearly parallel faults. Many of these have been mapped as high-angle reverse faults, with the Franciscan rocks overriding the Great Valley sequence and other rocks as young as Tertiary (Taliaferro, 1943b, pl. II). The system of high-angle reverse faulting is not clear, but if one accepts the interpretation of the faults shown on available maps and cross sections, the reverse faults of the Coast Ranges tend most commonly to follow the flanks and dip toward the axes of the major ranges. This pattern suggests crustal shortening from east to west, with a resulting elevation of horst-like mountain blocks between opposing reverse faults.

Thrust faults. Low-angle thrust faults have been described in some areas of the Franciscan but generally have been accorded little regional importance. The St. John Mountain thrust was described by Weaver (1949a, p. 137-139) as an essentially horizontal fault along which the Franciscan moved southward over the Great Valley sequence. According to the relations shown on Weaver's (1949a) maps and cross sections, the total displacement must be at least 5 miles. Rocks younger than Miocene are not involved in the thrusting, and much of the trace of the thrust has been covered by the Sonoma Volcanics of Pliocene age.

In the Orchard Peak area, 20 miles southeast of Parkfield and just east of the San Andreas fault, Marsh (1960) described Franciscan rocks and serpentine as having been squeezed plastically along the Aido Spring thrust. This thrust fault, which is one of several gently dipping imbricate thrust faults in the Orchard Peak area, has carried Lower Cretaceous(?) strata over Upper Cretaceous strata, and, although the stratigraphic throw is about 15,000 feet, neither the net slip nor the distance that the Franciscan rocks have traveled along the fault is known. The adjacent Antelope Valley thrust has carried Cretaceous strata over Miocene strata and is thought to have a net slip of at least 7 miles. Both these thrusts, which moved from north to south and are cut by a system of right-lateral tear faults, Marsh related to compression caused by right-lateral movement along the nearby San Andreas fault. He concludes that the thrusting occurred after late Miocene and before late Pliocene or early Pleistocene time. It is noteworthy that the thrusting in the Orchard Peak area is similar to that in the St. John Mountain area, about 225 miles to the northwest, and the views of Weaver (1949a) and Marsh (1960) regarding the age of thrusting are compatible.

The workings in quicksilver mines provide exposures that indicate thrusting may be rather widespread in the Coast Ranges. The following examples of thrust relations worked out in the mines show thrusting from the southwest in some cases and from northeast in others. These directions of thrusting contrast with the north to south thrusting ascribed to the St. John Mountain and Aido Spring thrusts, but most, if not all, of the thrusts described in mine reports seem compatible with regard to an age as young as Tertiary.

At the Rinconada mine, near Santa Margarita in the Pozo quadrangle, studied by Eckel, Yates, and Granger (1941, p. 567-568), Franciscan rocks have been thrust to the northeast at a low angle over Upper Cretaceous miogeosynclinal and Tertiary strata. At the Valley View mine, in the Panoche Valley quadrangle, Franciscan graywacke is cut by imbricate low-

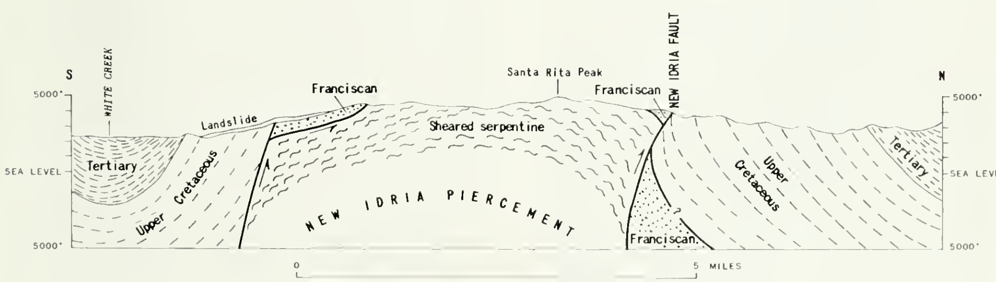


Figure 31. Cross section of New Idria area, after Eckel and Myers (1946, pl. 8).

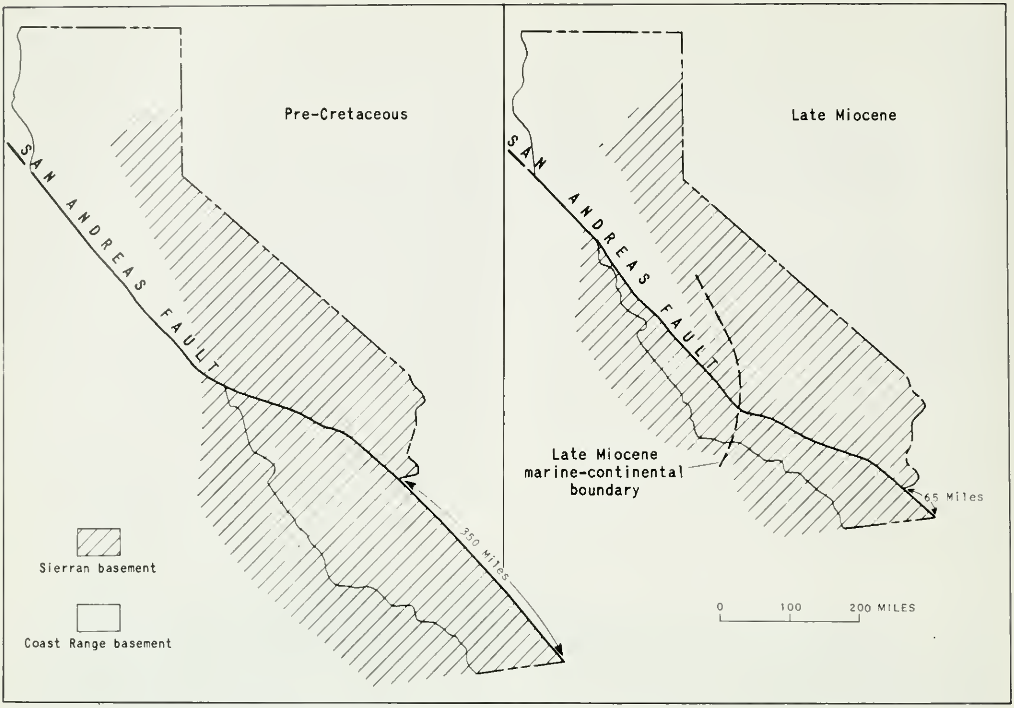


Figure 32. Palinspastic sketch maps of California showing conditions in pre-Cretaceous time, before postulated 350-mile offset of Sierran basement along San Andreas fault, and in late Miocene time as shown by Hill (1954, p. 12, fig. 3).

angle thrust faults that trend north and dip east (Yates and Hilpert, 1945). At the Helen mine, in the Calistoga quadrangle, Franciscan sedimentary rock has been thrust northeast over serpentine, but at the Corona mine in the same quadrangle, serpentine has been thrust northeast over Franciscan sedimentary rock (Yates and Hilpert, 1946).

HYPOTHESES TO EXPLAIN PRESENT DISTRIBUTION OF MESOZOIC ROCKS OF THE COAST RANGES

As is indicated in the preceding sections, data accumulated in the last 20 years leads to a much clearer understanding of the present distribution of the assemblage of Franciscan rocks, the environment in which these rocks formed, and the relations between them and the Great Valley sequence. Even so, perplexing problems arise when one attempts to reconstruct the paleogeography or to work out the history of the depositional and tectonic events that have resulted in the present distribution of these two coeval assemblages.

Problems

Some of the major problems that need explanation arise from uncertainty regarding the history of the long block of crystalline rock lying between the San Andreas and Nacimiento faults. For example: (1) Is the block of crystalline rock in approximately the same place it was when the Franciscan and Great Valley sequence were deposited, or has it been moved into its present position by major tectonic dislocations since the deposition of the two assemblages? If it is allochthonous, when did it move, and from where has it moved? (2) What kind of rock, if any, was being deposited on this block in Late Jurassic or Early Cretaceous time? (3) Why do the latest Cretaceous miogeosynclinal rocks just east of granite exposures in the crystalline block, but separated from them by the San Andreas fault, contain only fine detritus, while rocks of similar age on the block contain large granitic boulders? (4) If the granite is really of mid-Cretaceous age, as indicated by radiometric ages, why does the granite neither intrude nor metamorphose the older rocks of the Franciscan or Great Valley sequence? (5) Does some, or all, of the Franciscan rest

on metamorphosed rocks similar to those exposed in the block, or does the Franciscan lie directly on a basaltic substratum, or on the mantle? (6) Why is intrusive ultramafic rock so widespread in the Franciscan but so sparse both in the block of crystalline rocks and in the Great Valley sequence? (7) What relation does the great easterly trending Mendocino escarpment have to the San Andreas and Nacimiento faults, or to the other northwest-trending Coast Range structures?

Even if the crystalline block were not present, there would remain other equally perplexing problems that involve neither the San Andreas fault nor the granite. For example: (1) Why are the Franciscan and Great Valley facies in most areas so clearly different, and why are there so few places where one finds relations that might be considered to be gradational? (2) Why is the contact between the two major facies generally a fault or a serpentine mass? (3) Why do we find fossiliferous strata of the Great Valley sequence in the Healdsburg area adjacent to younger and perhaps older and contemporaneous Franciscan eugeosynclinal rocks, and why are these miogeosynclinal strata so mildly deformed as compared to the younger Franciscan rocks adjacent to them? (4) Why do we have a thick section of Upper Jurassic and Cretaceous miogeosynclinal rocks in the Diablo Range extending west to the Hayward fault, yet only a few miles west of the Hayward fault there are vast volumes of eugeosynclinal Franciscan rocks containing many fossils of mid-Cretaceous age but with no indication of intergradation between the two assemblages? (5) Why in the area north of Clear Lake are the Lower Cretaceous rocks of the Franciscan apparently devoid of K-feldspar, whereas only a few miles to the east rocks of identical age in the Great Valley sequence contain small but persistent amounts of K-feldspar?

These questions indicate there is no simple solution to the problems posed by the present distribution of the Franciscan and Great Valley sequence, but the recognition of these problems must be the first step toward their solution. Various suggestions involving movement along the San Andreas and Nacimiento faults have been presented by geologists to explain the anomalous corridor of metamorphic and granitic rocks that cuts through the Coast Ranges at a low angle, but many of the other questions raised have not been seriously considered because they were not recognized, chiefly because the post-Knoxville age of part of the Franciscan has only recently been generally recognized. In the following paragraphs we will offer for consideration several contrasting ideas of the depositional and tectonic history of the Franciscan, each of which has some merit in that it explains some of the problems but also is unsatisfactory in that it fails to solve them all.

Strike-slip Hypothesis

If one attempts to draw a series of paleographic maps that does not take into account major structural dislocations during or since the deposition of the Upper Jurassic to Upper Cretaceous rocks, it becomes obvious that the present distribution of these rocks cannot be explained adequately by simple facies changes. As rocks of similar ages but of different facies are now adjacent to each other, but show no intergradation, their present distribution must be explained by some kind of tectonic displacement. Such displacement may result from strike-slip faulting, thrust faulting either with or without later normal faulting, or gravity sliding on a large scale. Owing to the known presence of strike-slip faults of large displacement in the Coast Ranges (see fig. 29), one is tempted to try to explain all the relations by strike-slip displacement, but, as will be discussed, some aspects of the present distribution of rocks seem more readily explained by diagonal rifting or thrust faulting.

The best known strike-slip fault in California is the active San Andreas fault along which there have been several tens of feet of right-lateral displacement in historic time (Wallace, 1949, p. 799) and along which stream canyons have been similarly displaced a few miles since the beginning of Quaternary time. The sense and amount of total displacement, or when the fault originated, is less well established. Hill and Dibblee (1953) and Hill (1954) have marshalled evidence to indicate that movement has occurred at a fairly constant rate since the intrusion of the Sierra Nevada batholith (then thought to be Jurassic but now believed to be largely mid-Cretaceous) with a total displacement of about 350 miles (fig. 32). King (1959, p. 170-173) has used a modification of this concept to explain the distribution of the Franciscan rocks and granitic block west of the San Andreas fault, but he has not related the required large movements to any particular time. Carey (1958, p. 192, 336-338) has suggested that the main branch of the San Andreas fault extends into the Gulf of California and that the block west of the fault is displaced not only for hundreds of miles northward but also laterally in the southern part, so that Baja California has drifted westward from a former position adjoining the Mexican mainland. Hamilton (1961) has supported and offered further documentation for this suggestion.

To best visualize the effect of an offset of 300 miles or more, it is helpful to cut a geologic map along the San Andreas fault and restore the pre-fault geology by sliding one part past the other. When this is done it is quite apparent that the parts will not fit in the displaced position unless one assumes more bending of the crust than seems to be indicated by the younger sedimentary strata. (Note on figure 32, a large area on the western block seems to have disappeared between the pre-Cretaceous and late Miocene.) However, allowing for some adjustment to achieve a fit, the

effect of a restoration of conditions prior to a displacement of 300 miles is to move the Nacimiento-west area of Franciscan back to a supposed original position near the present coast south of San Diego, and the Franciscan rocks now exposed on Catalina Island and in the Palos Verdes Hills to near the present crest of the Sierra San Pedro Martir in Baja California. This amount of movement would account for the presence of the crystalline San Andreas–Nacimiento block far from its seemingly normal position along the Sierra Nevada trend, it would improve the continuity of the quartz diorite line proposed by Moore (1959), and, if the movement is post-Cretaceous, it would explain why the Cretaceous rocks of the San Joaquin Valley seem to lack debris from the crystalline block. However, despite the appealing solution offered by postulated large lateral offsets, serious objections to this hypothesis can be raised. For example, such large movements along the San Andreas fault seriously disrupt the present striking alignment of the core of the Sierra Nevada–Baja California batholith and, as noted by Woodford (1960, p. 414), seem to create more problems than they solve regarding the distribution of pre-Franciscan rocks in southern California. Equally serious is the fact that although the continental margin appears to be displaced westward along the Mendocino escarpment, which seems to be a logical northwestern extension of the San Andreas fault, this displacement is less than 75 miles rather than more than 300 miles. Nonetheless, the evidence set forth by Noble (1954), Hill and Dibblee (1953), and Hall (1960) suggests a right-lateral offset of about 50 miles since late Miocene in the area near the southern end of the San Joaquin Valley, and Crowell (1960) makes a good case for a 160-mile combined displacement of pre-Franciscan basement rocks on the San Andreas and San Gabriel faults in southern California.

Because nearly all the Franciscan rocks lie east of the San Andreas fault and west of the Nacimiento fault, in most places they provide no direct evidence for movement on the San Andreas fault. However, on the San Francisco peninsula there is a unique wedge of Franciscan rocks, west of the San Andreas fault and east of the Pilarcitos fault (fig. 29), which diverges northwestward from the San Andreas. Within this wedge the Franciscan Formation contains lenses of the fossiliferous Calera Limestone Member of mid-Cretaceous (Albian-Turonian) age trending southeast from Rockaway Beach, on the coast, to the vicinity of Crystal Springs Lake, which lies in the trench of the San Andreas fault. According to the map of Walker (1950), the limestone on the east side of the San Andreas fault begins at a point about 15 miles southeast of where it reaches the fault from the west. Because of the presence of other faults lying east of and parallel to the San Andreas, and apparently part of the same system, the 15 miles measured here is not the total displacement along the zone. The same limestone is systematically offset by several other faults in a right-lateral sense until it reaches its southernmost occurrences in the San Juan Bautista quadrangle, and the aggregate displacement across the entire zone is between 35 and 50 miles. This apparent measure of offset along the San Andreas fault can be nullified if, as has been suggested, the main movement occurred along the Pilarcitos fault, and if this fault extends northward beneath the ocean to rejoin the San Andreas fault east of Point Reyes. This conjecture would, however, require a sharper bend than is found elsewhere along the San Andreas fault. Moreover, according to Earl Brabb (oral communication, 1960), the stratigraphic column and geologic history from Late Cretaceous through the Oligocene is remarkably similar, even in detail, in areas west of the Pilarcitos and east of the San Andreas fault in this area, indicating the aggregate post-Late Cretaceous offset along both faults is not likely to be hundreds of miles. Higgins (1961), on the basis of marine entrances to middle Pliocene basins across the fault north of San Francisco, estimates the displacement along the San Andreas since the middle Pliocene has not exceeded 15 miles and may have been not more than 1 to 1½ miles.

Thus, it is apparent that data can be cited to indicate different amounts of movement for various parts of the fault. To the north, the offset of the continental margin on the Mendocino escarpment suggests a displacement of less than 75 miles; offset of Franciscan limestones in the Bay area suggests a post-Franciscan displacement of 50 miles or less; offset of upper Miocene rocks near the south end of the San Joaquin Valley is about 50 miles, and a total displacement of as much as 160 miles or more may have occurred in southern California.

One might account for the relatively small offset along the San Andreas fault in the San Francisco Bay area by postulating earlier strike-slip faulting along the trend of the Hayward fault. This mechanism can be used to explain the juxtaposition of the coeval Franciscan and Great Valley sequence in the vicinity of the San Francisco peninsula and the Berkeley Hills. Similarly, the block of fossiliferous Great Valley sequence near Healdsburg may be a large sliver caught up and dragged along this fault from a previous position somewhere to the south. North of Healdsburg the nature of the faults forming the eastern border of the coastal belt rocks has not been established, but perhaps these faults mark a continuation of the Hayward fault zone that has been modified by later, cross-cutting faults.

Oblique-rifting Hypothesis

A quite different hypothesis, involving a combination of moderate strike-slip movement and oblique rifting, seems to answer some of the problems of distribution while avoiding difficulties inherent in the large-scale strike-slip mechanism. To develop this hypothesis we assume that the crystalline block be-

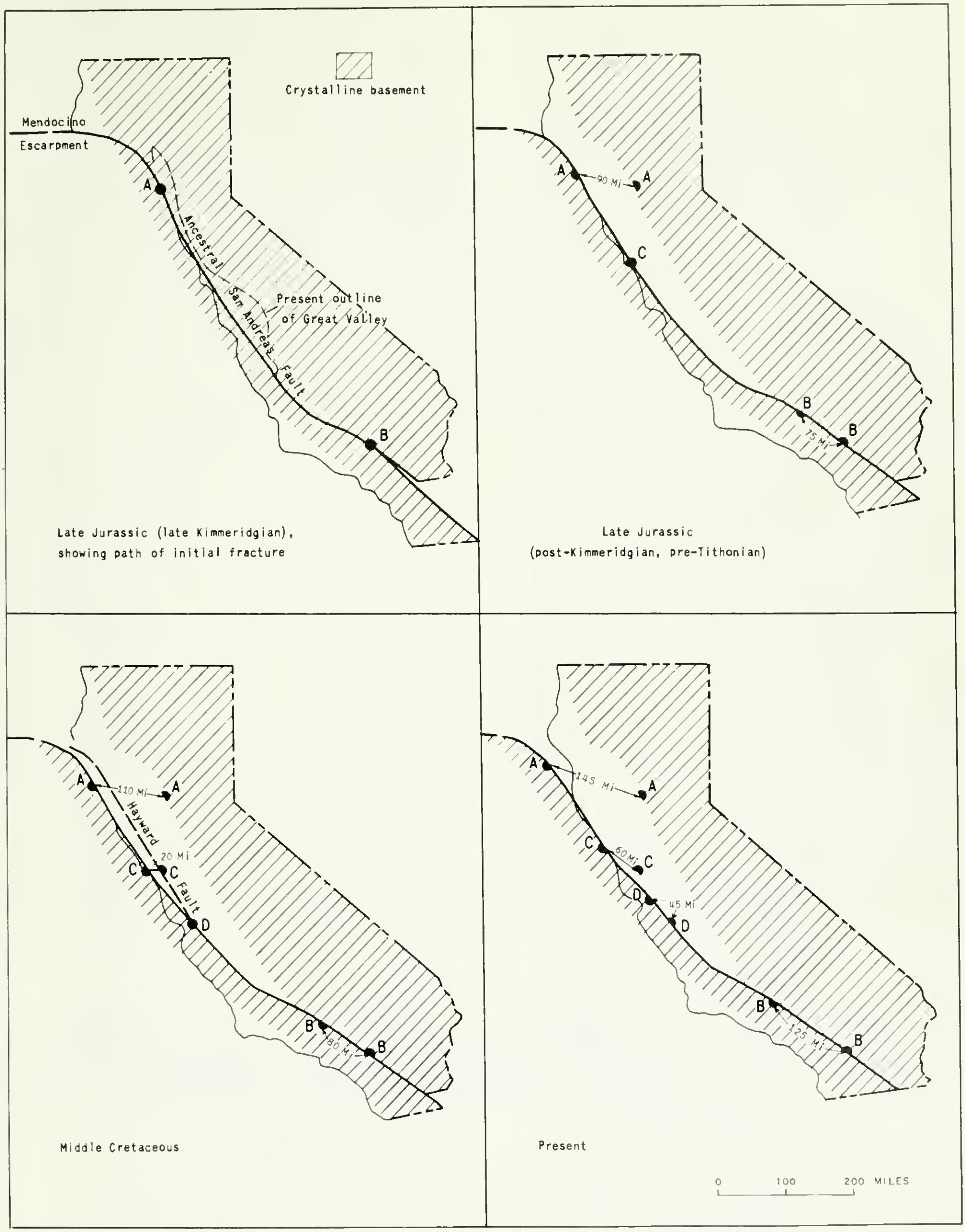


Figure 33. Palinspastic sketch maps of California showing postulated oblique rifting of Sierran basement since Late Jurassic time.

tween the San Andreas and Nacimiento faults has drifted laterally from a position adjacent to the present central part of the Great Valley, in much the same manner as has been postulated for the separation of Baja California from the Mexican mainland (fig. 33). The San Andreas fault, which marks the eastern margin of the drifting block, has also shifted its position relative to the mainland through geologic time. The San Andreas fault in its original position formed an arc, beginning on the west at its northern end along the path of the Mendocino escarpment and proceeding eastward along the west-northwesterly fault that abruptly cuts off the southern end of the Klamath Mountains. Then, swinging more southward, it trended through the Great Valley, approximately along the large magnetic high (Irwin and Bath, 1962) that marks the west edge of the Klamath Mountain-Sierra Nevada crystalline rocks. It would have a nearly straight path to the central part of the southern end of the Great Valley and would extend onward to join the present position of the San Andreas fault to the south. The western margin of the crystalline block prior to offset cannot be fixed with certainty, but it has been sketched in on figure 33 so that it extends from the present western margin in northern California along a gentle arc, generally parallel to the ancestral San Andreas fault, to the Newport-Inglewood fault, which in southern California separates a pre-Franciscan basement from metamorphosed Franciscan rocks.

The initial rupture and pulling apart along this ancestral San Andreas fault probably occurred after the folding of the Galice and Mariposa Formations in late- or post-Kimmeridgian time and proceeded rapidly so that by Valanginian time the eastern margin of the westerly drifting block lay near the present position of the Hayward fault. As the northern end of the crystalline block is arcuate, this movement would result in the opening of a marine trough extending from near Eureka to the southern end of the San Joaquin Valley; south of this point, a right-lateral offset of some 75 miles along the San Andreas fault would be required. The drifting away of a crustal block provides a site of deposition for Franciscan rocks of pre-Knoxville age, and if the crustal block slid at the surface of the basaltic substratum, the Franciscan in this area was deposited directly upon this surface. As this trough filled with sediments derived from the erosion of the metamorphic rocks to the east, accompanied locally by submarine volcanic accumulations, it would shoal from the narrow southern end and from the east. By Knoxville (Tithonian) time, miogeosynclinal sediments were being deposited chiefly in the area east of a line drawn from near San Luis Obispo to a point near the middle of the Paskenta quadrangle, but in the earliest part of this period, volcanism accompanied Knoxville sedimentation in local areas; west of this boundary in northern California, Franciscan sediments were being deposited. Owing to the subsequent uplift and accompanying erosion of the block between the San Andreas and Nacimiento faults, no known Tithonian sediments remain on this block, though they may once have been present. In Valanginian time similar conditions existed except that strata of the Great Valley sequence were deposited on the eroded Klamath Mountains block.

Prior to Albian time the drifting block seems to have again shifted westward, nearly to its present position, providing a second trough that extended from the San Francisco area northward. In this trough the mid-Cretaceous Franciscan rocks were deposited. The western limit of the Great Valley sequence continued to shift westward in northern California, but in the Diablo Range we find Albian miogeosynclinal rocks only north of the latitude of Mount Hamilton and south of New Idria. The intervening area may have been the source for the San Francisco Bay area mid-Cretaceous Franciscan rocks, which have an unusually sparse K-feldspar content as compared to coeval strata of the Great Valley sequence.

From Cenomanian to late Campanian, conditions seem to have been relatively stable. The Franciscan trough on the San Francisco peninsula may have shoaled, as is indicated by the presence of oölitic limestone, but volcanic activity persisted. In the northern Coast Ranges volcanic activity subsided greatly, and shoaling of the area led to the deposition of the rocks of the "coastal belt" with sedimentary characters somewhat intermediate between the typical Franciscan and Great Valley sequence. Also during this interval granitic rocks were formed in the Sierra Nevada and in the displaced Coast Range block.

Subsequent to the Campanian, no eugeosynclinal rocks were deposited, but the crystalline block between the San Andreas and Nacimiento faults was uplifted and stripped of all pre-Maestrichtian sediments that may have been deposited on it. Miogeosynclinal rocks were then deposited directly on the eroded surface of this crystalline block and on areas both east and west of it. With the uplift of the crystalline block there probably was some additional right-lateral offset along the San Andreas fault, but this has not been established. Subsequent to the middle Miocene an accumulated offset of about 50 miles seems to be fairly well established for the southern half of the fault, but perhaps an appreciable part of this movement in northern California took place along the Hayward or other branching faults.

The geologic history of the block west of the Nacimiento fault has scarcely been touched upon in this discussion, chiefly because so little is known about the ages of the Franciscan and Great Valley sequence in it. The Franciscan of this area may well have been deposited in a wedge-shaped trough formed by a southward lateral shift of part of the crustal block, but, if so, we cannot establish when this rupture took place.

This hypothesis involving both lateral drifting and strike-slip movement appears to account for the un-

usual development of a eugeosyncline between an offshore crystalline mass and a continental block, for the apparent lack of normal sedimentary or crystalline basement beneath the Franciscan, for the various ages represented by the Franciscan, and for most of the relations now existing between the eugeosynclinal Franciscan and coeval miogeosynclinal Great Valley sequence. This hypothesis also explains how the San Andreas fault can have a different offset at different points along it and, perhaps, how this fault originated and how it is related to the great submarine Mendocino escarpment. The path of initial rupture would extend along the crest of the East Pacific Rise of Menard (1960), and one might attribute the westward movement of the block to its sliding off of the Rise. This oblique-rifting hypothesis, however, does not explain the occurrence in the northern Coast Ranges of Upper Jurassic and Lower Cretaceous Franciscan graywackes with no K-feldspar just west of the serpentine belt and coeval graywacke with K-feldspar in the Great Valley sequence just east of the serpentine belt; nor does it explain why transitions from one facies to the other seem to be so abrupt.

Thrust-faulting Hypothesis

An alternative or modifying hypothesis, involving thrusting or gravity sliding along some of the serpentine masses, would aid in explaining some relations that cannot be accounted for by movements on the major steep faults. Although no large-scale overriding of the Franciscan by rocks of the Great Valley sequence can be proven by the available data, there are so many factors suggesting the possibility that it should be seriously considered. Two principal factors suggestive of the possibility of large-scale thrusting or gravity sliding are: (1) the common occurrence of serpentine as an intervening sheet beneath the Great Valley sequence but above the Franciscan, and (2) the juxtaposition of coeval rocks of different facies and tectonic style.

Most of the serpentine masses of western California are in areas containing the eugeosynclinal assemblage of Franciscan rocks, but such masses are not uniformly distributed in these areas as a disproportionate number are along, or in some cases only near, contacts between the Franciscan and strata of the Great Valley sequence. This spatial relation suggests that, particularly in northern California, much of the serpentine once was a part of a continuous subhorizontal sheet of serpentine lying beneath the Great Valley sequence. The most continuous exposure of this sheet is where serpentine crops out as a belt along the west side of the northern Great Valley; for a length of about 70 miles the serpentine generally separates the Franciscan to the west from the Great Valley sequence to the east (pl. 1). Along the southern extension of this belt, from the Wilbur Springs quadrangle nearly to the San Francisco Bay area, almost contiguous bodies of serpentine that likely are dislocated segments of the same mass have similar structural relations. A few miles north of the Bay area the general trend of the discontinuous exposures of serpentine swings to the west forming a map pattern that seems to result from the broad, southeasterly plunging fold we have termed the Diablo antiform. The present somewhat discontinuous character of the serpentine bodies here, and the patchy exposure of the overlying strata of the Great Valley assemblage in the broad crest of the Diablo antiform, is attributed to folding, to renewed flowage into secondary structures, and to younger steep northwest-trending faults superimposed on the antiform. Farther south along the antiform, in the Diablo Range, serpentine accompanies the other Franciscan rocks in piercements pushed up through the strata of the Great Valley sequence.

The idealized vertical section (fig. 34) through Lower Lake and Morgan Valley quadrangles shows the foregoing relations. Here the general continuity of the overlying strata of the Great Valley sequence across a major portion of the Coast Ranges is evident, and an even greater former continuity is suggested when one relates these strata to outliers of the Great Valley sequence that lie even farther southwest (fig. 35). The strata of the Great Valley sequence seemingly are separated from the underlying Franciscan rocks by a sheet of serpentine that is a deformed but essentially subhorizontal westward extension of the more steeply dipping mass of serpentine that crops out

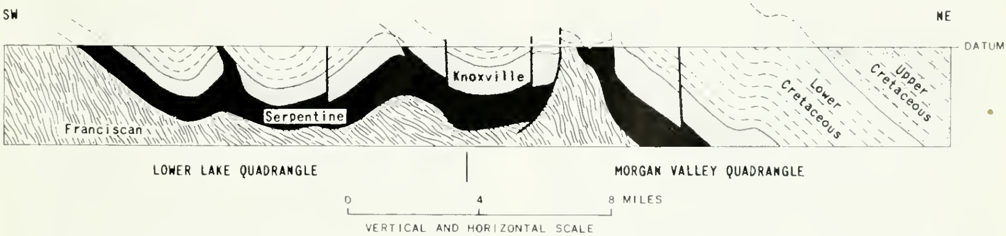


Figure 34. Idealized vertical section across parts of Lower Lake and Morgan Valley quadrangles. Geology based on maps by Brice (1953) and Lawton (1956), and not adjusted for topography.

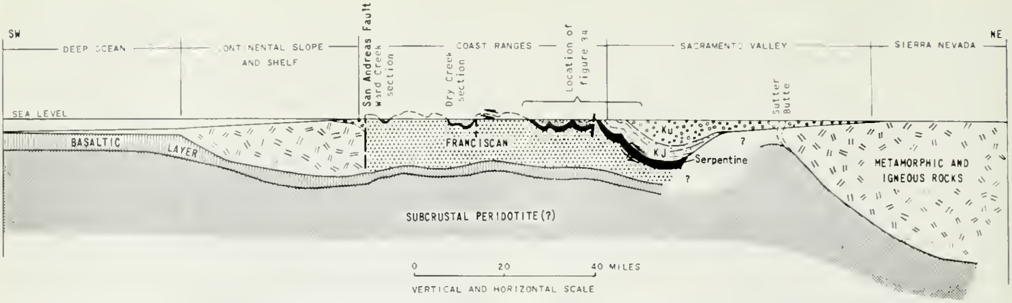


Figure 35. Idealized vertical section across western California and offshore area. Line of section trends southwest through Sutter Buttes and crosses coastline near Fort Ross. Diagram illustrates hypothesis of Upper Cretaceous (Ku), Lower Cretaceous, and Upper Jurassic (KJ) of Great Valley sequence thrust over the Franciscan, with serpentine along thrust zone.

in the same structural or stratigraphic position for a great distance along the west side of the Sacramento Valley. In the eastern part of the Coast Ranges, along the line of sections (figs. 34 and 35), the serpentine mass seems fairly continuous, but in the western part, in the vicinity of the Dry Creek and Ward Creek sections (fig. 35) the serpentine occurs between the two assemblages only in a few places.

An eastern root zone for the serpentine sheet is indicated by the large size and continuity of the serpentine body along the east limb of the Diablo antiform, and by large magnetic anomalies. A large magnetic high coincides with the serpentine exposed along the east limb of the Diablo antiform (Irwin and Bath, 1962), but this anomaly is paralleled by an even greater magnetic high that follows the central part of the Great Valley (fig. 29). The Great Valley anomaly seems to indicate the presence of a large ultramafic body buried at a depth of 5 miles or more, and the serpentine belt along the east limb of the Diablo antiform could well be the exposed westward extension of such a body.

If the concept of the sheetlike occurrence of the serpentine between the miogeosynclinal strata and Franciscan is correct, the "sedimentary serpentine" found in Wilbur Springs and other areas may be a part of this sheet extruded through a rupture in the Knoxville strata onto the sea floor in Early Cretaceous time. This kind of origin is in contrast to the landslide origin postulated by some, which requires the existence of large topographic highs of serpentine adjacent to an area in which dominantly clay shales were being deposited (Taliaferro, 1943a, p. 207).

The second factor suggesting thrust faulting, that of juxtaposition of coeval rocks of different facies and tectonic style, includes two situations—where the rocks are one above the other, and where they are merely adjacent. Where rocks of the Great Valley sequence overlie the Franciscan, it would be reasonable to assume that they owe their position to thrusting if the underlying Franciscan rocks are the younger. Although some Franciscan rocks are established paleontologically as Late Jurassic to Late Cretaceous in age, the age of the Franciscan rocks that actually lie below strata of the Great Valley sequence is not known. Thus, the superposition of the Great Valley sequence on the Franciscan cannot be viewed as an indication of large-scale thrusting or gravity sliding unless the age of the Franciscan at that specific locality is established paleontologically as equivalent or younger than the overlying strata. On the other hand, the juxtaposition of the Dry Creek and Ward Creek sections of Upper Jurassic and Lower Cretaceous miogeosynclinal strata adjacent to younger, and perhaps also older, Franciscan rocks can be conveniently explained by thrusting (see fig. 35). These juxtaposed assemblages were derived from different sources and deposited in different environments, as is indicated by their contrasting content of K-feldspar and by their lithology; that they also have a different geologic history is indicated by the fact that the strata of the Ward Creek and Dry Creek sections are much less folded and faulted than the adjacent younger Franciscan rocks. Clearly the two facies have been brought together tectonically, but whether this was done by thrust faulting, gravity sliding, or strike-slip faulting is not yet clear.

In summary, the gross contemporaneity of the Franciscan and the Great Valley sequence, and the general separation of the two facies by serpentine over broad areas, make attractive a working hypothesis of low-angle dislocation of great magnitude. Perhaps some of the enormously thick Upper Jurassic and Lower Cretaceous part of the Great Valley sequence glided westward off an ancient continental shelf and slope now occupied by the eastern part of the Great Valley and western part of the Sierra Nevada as an essentially cohesive and little-deformed mass. The ease of movement across the bordering Franciscan may have been enhanced by synchronous extrusion of serpentine along the edge of the continental mass. Or, alternatively, the Franciscan rocks may have been carried eastward beneath the Great Valley sequence by east-

ward-moving subcrustal currents that plunge under the continental crust. The ramifications of the thrust hypothesis are many, and one interesting aspect is with regard to the distribution of some of the metamorphic rocks of the Franciscan. The thrusting might have promoted the development of the phyllite and jadeite along the eastern side of the Coast Ranges, and some of the tectonic blocks of glaucophane schist farther west may be erratics that were dragged upward from depth along a thrust zone.

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QUATERNARY
AND
TERTIARY

EXPLANATION

Qt — Sedimentary and volcanic rocks (QUATERNARY AND TERTIARY)

EUGEOSYNCLINAL FACIES

Franciscan rocks (Upper Jurassic – Lower Cretaceous – Upper Cretaceous)

Coastal belt dominantly graywacke, shale, and conglomerate

Graywacke, shale, conglomerate, mafic volcanic rocks, chert, minor limestone, and metamorphic rocks

MIOGEOSYNCLINAL FACIES

Great Valley sequence

Graywacke, feldspathic sandstone, shale, conglomerate, and thin limestone beds. Locally has mafic volcanic rocks and chert in lower part of Jv

INTRUSIVE ROCKS

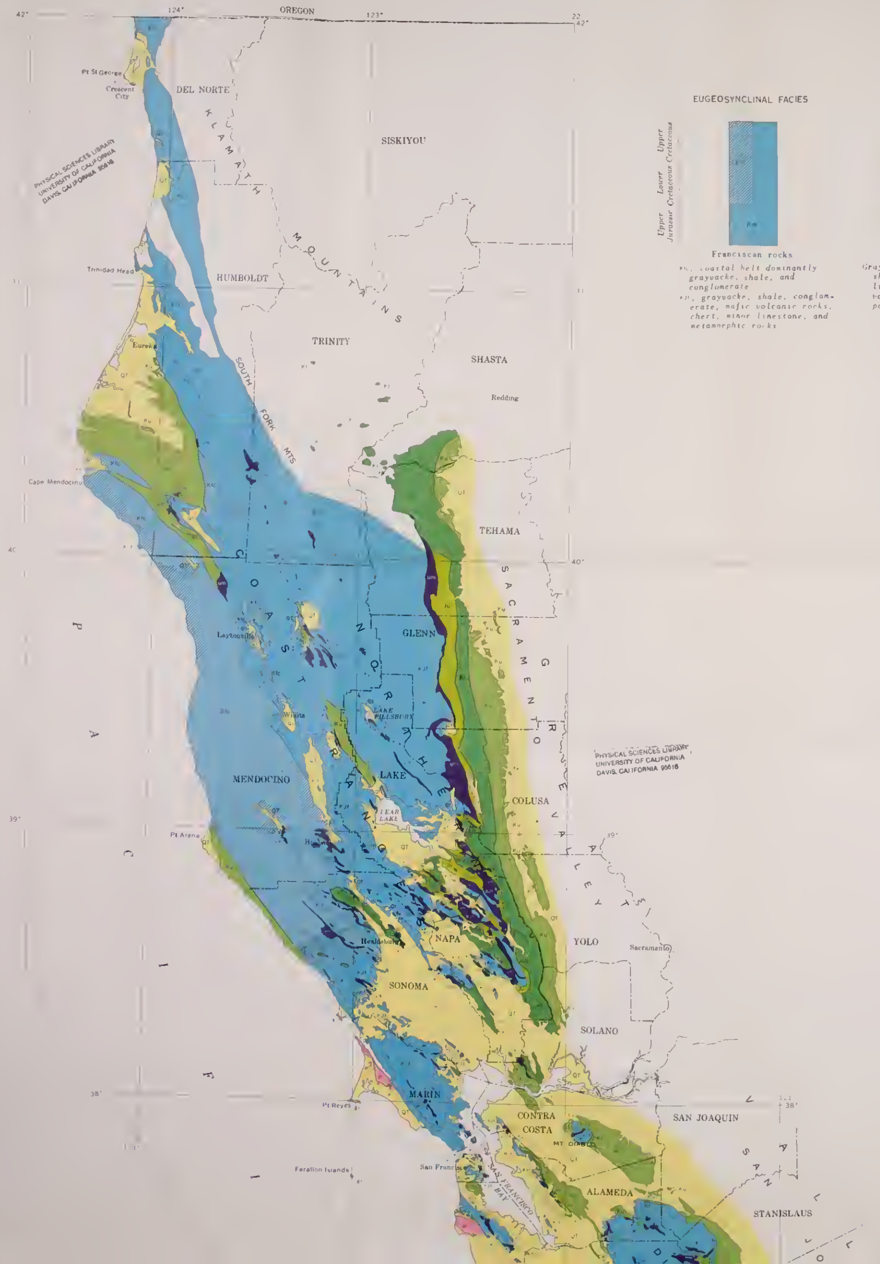
Granitic rocks, chiefly quartz diorite, granodiorite, and quartz monzonite

Ultramafic rocks, chiefly serpentinite. In text treated as part of the assemblage that includes the Franciscan Formation

METAMORPHIC ROCKS

Metamorphic rocks of the Nacimiento-San Andreas block and Transverse Ranges. Pre-latest Jurassic in age

QUATERNARY AND TERTIARY — CRETACEOUS — JURASSIC — PALEOZOIC



INDEX MAP OF CALIFORNIA SHOWING DISTRIBUTION OF COAST RANGES, GREAT VALLEY, KLAMATH MOUNTAINS, SIERRA NEVADA, AND TRANSVERSE RANGES. DISTRIBUTION OF FRANCISCAN ROCKS SHOWN BY COLORED AREAS

INDEX MAP OF CALIFORNIA SHOWING SOURCES OF DATA
USED IN COMPILING GEOLOGIC MAP

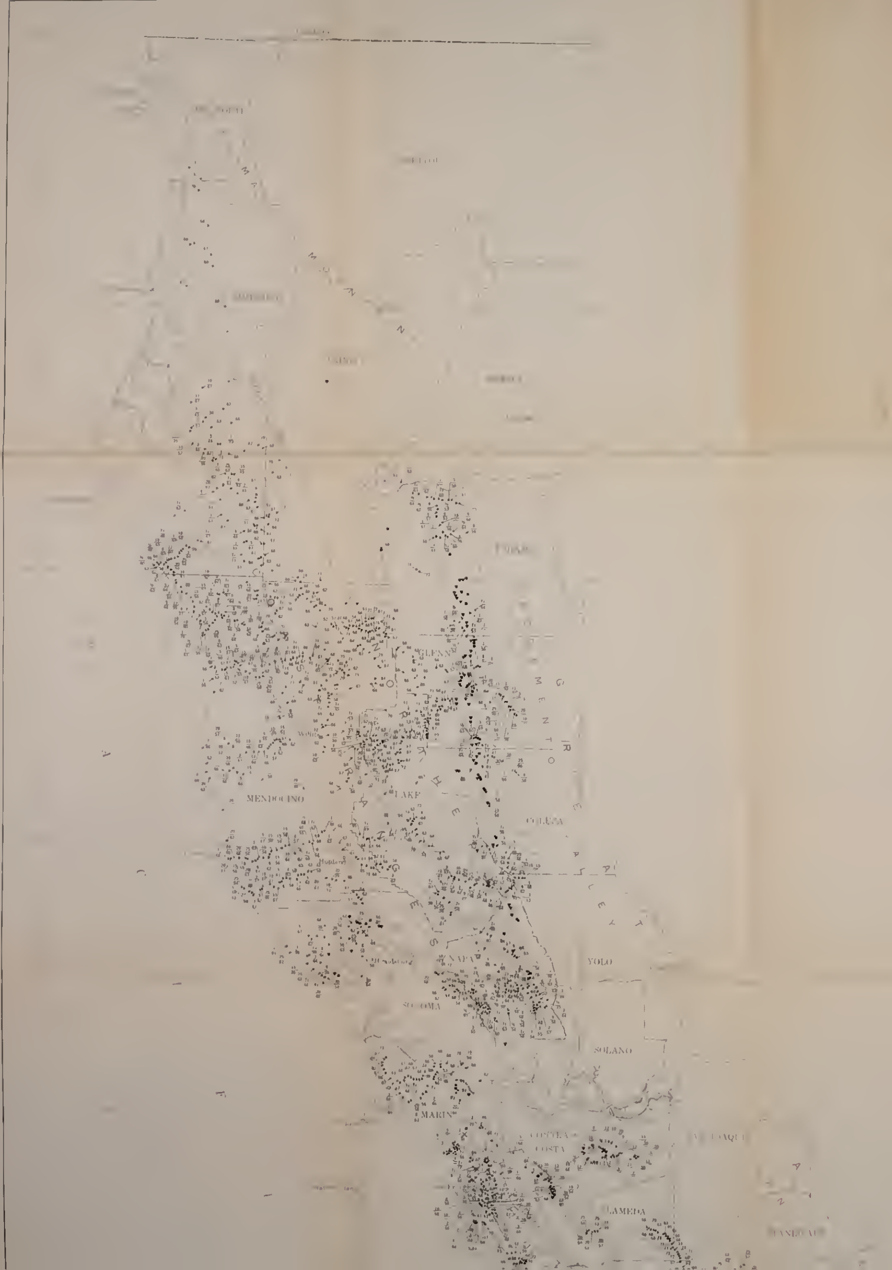
Sources of data used in compiling the geologic map All compiled data have been modified Numbers correspond to those shown on index map

1 Irwin, 1960
2 Ukiah Sheet, Geologic map of Calif Olaf P Jenkins Edition Calif Div Mines, 1960
3 Santa Rosa Sheet, Geologic map of Calif , Olaf P Jenkins Edition, preliminary compilation, Calif Div Mines, unpub
4 Bailey, E H , Cazadero quadrangle, U S Geol Survey, unpub.
5 San Francisco Sheet, Geologic map of Calif , Olaf P Jenkins Edition, preliminary compilation, Calif Div Mines, unpub.
6 Includes Crittenden, M D., Jr , 1951, Hall, C A , Jr., 1958, Huey, A S , 1948, Bailey, E H , and Everhart, D L , in press, Ivan Colburn, 1961, Dibblee, T W , Jr , Loma Preita area, unpub , Maddox, M E., 1955, and Schilling, F A , Jr , 1962
7 Santa Cruz Sheet, Geologic map of Calif , Olaf P Jenkins Edition, Calif. Div Mines, 1959
8 San Luis Obispo Sheet, Geologic map of Calif , Olaf P. Jenkins Edition, Calif Div Mines, 1959
9. Bakersfield Sheet, Geologic map of Calif , Olaf P. Jenkins Edition, (Preliminary uncolored edition), Calif Div. Mines, 1955
10. Santa Maria Sheet, Geologic map of Calif., Olaf P Jenkins Edition, Calif. Div. Mines, 1959
11 Los Angeles Sheet, Geologic map of Calif., Olaf P. Jenkins Edition, (Preliminary uncolored edition), Calif Div Mines, 1955
12 Long Beach Sheet, Geologic map of Calif , Olaf P Jenkins Edition, (Preliminary uncolored edition), Calif Div Mines, 1955

Base modified from U. S. Geological Survey map of State of California, scale 1:500,000 edition of 1951

Geology compiled by W. P. Irwin, 1962

GEOLOGIC MAP OF WESTERN CALIFORNIA SHOWING DISTRIBUTION OF THE FRANCISCAN AND RELATED ROCKS



EXPLANATION

Megafossil localities

x
Fossils of mid and latest Cretaceous

Buchia crassicollis (Early Cretaceous)

Buchia piochii (Late Jurassic)

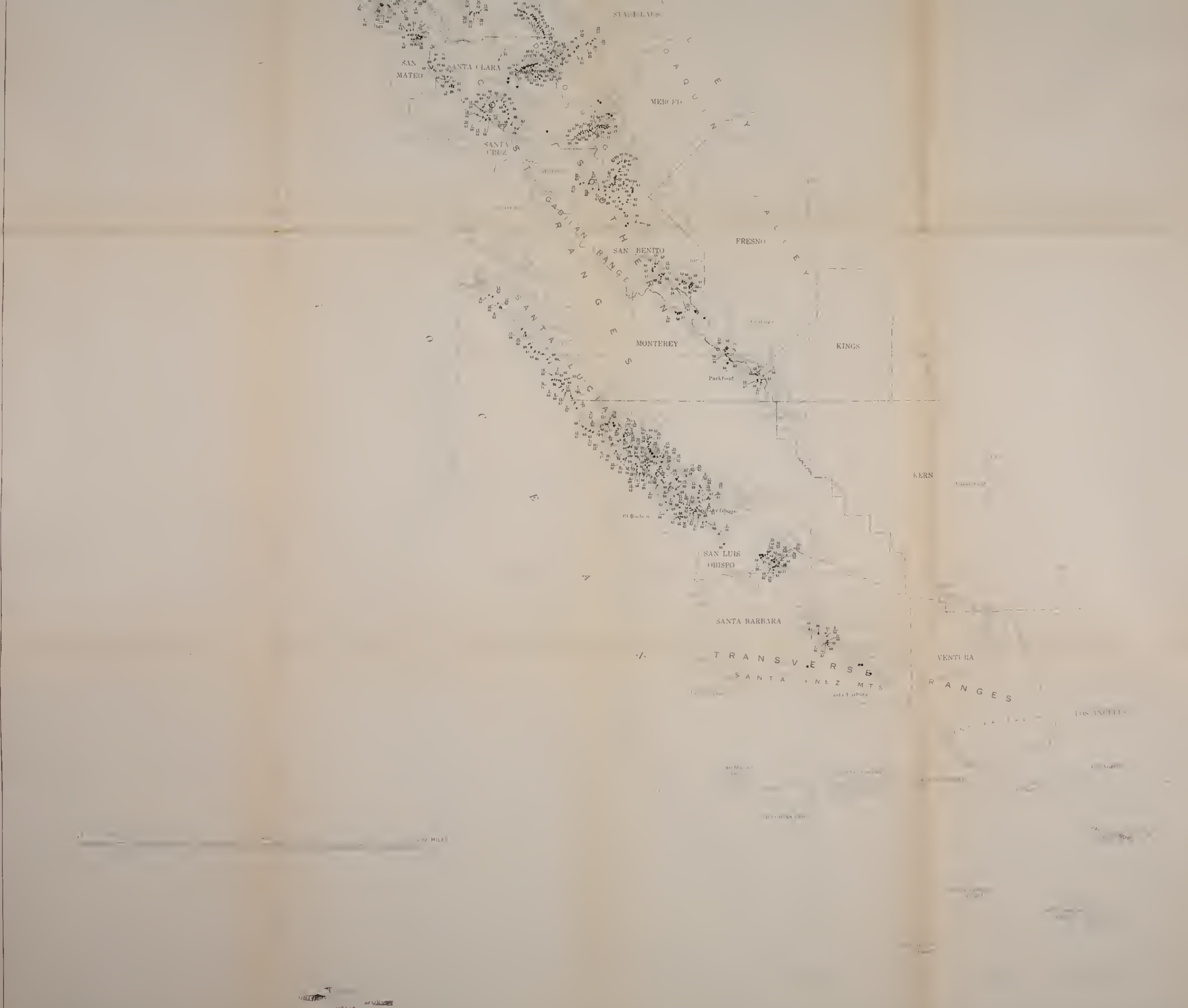
Localities of graywacke samples tested for K-feldspar content and for specific gravity

2 percent K-feldspar, 2.68 specific gravity

5 percent K-feldspar, no specific gravity data

0 percent K-feldspar, 2.57 specific gravity

0 percent K-feldspar, no specific gravity data



MAP SHOWING MEGAFOSSIL LOCALITIES, AND K-FELDSPAR CONTENT AND SPECIFIC GRAVITY OF UPPER MESOZOIC SEDIMENTARY ROCKS IN WESTERN CALIFORNIA